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Transforming food systems in Latin America and the Caribbean: increasing sustainability, resilience and adaptation to climate change

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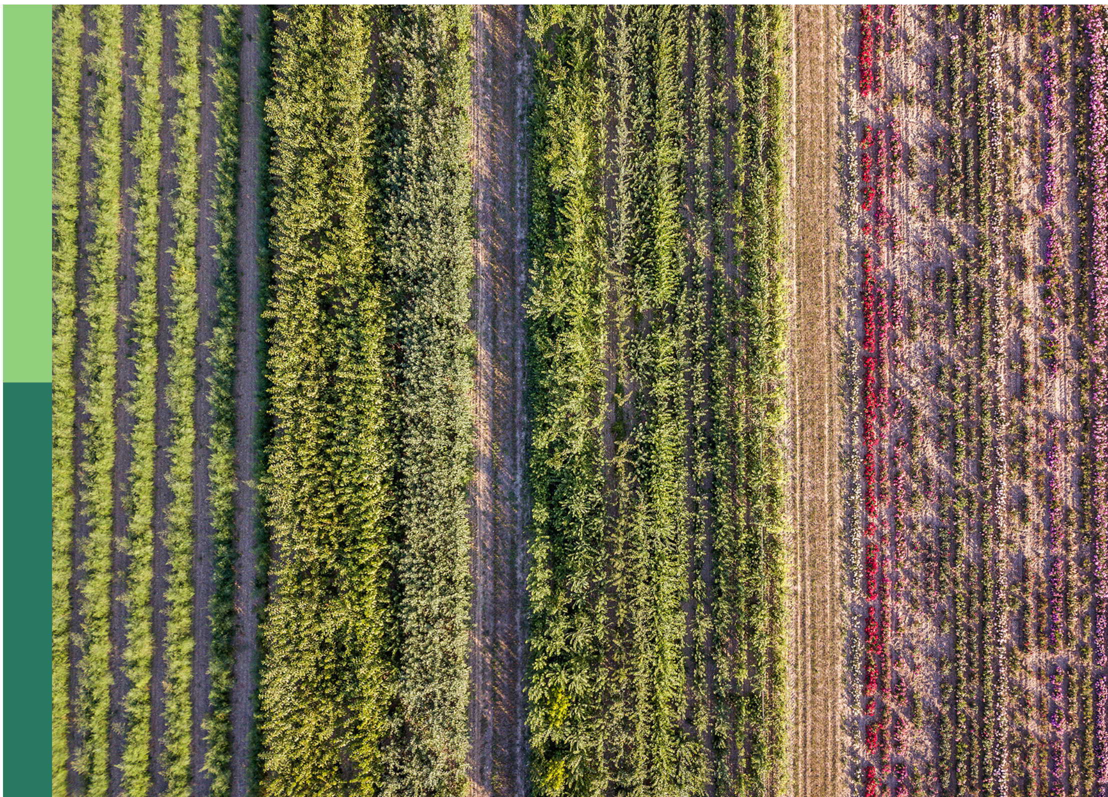

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Transforming food systems in Latin America and the Caribbean: increasing sustainability, resilience and adaptation to climate change

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Interactions between climate, shade canopy characteristics and cocoa production in Colombia

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Properly designed agroforestry systems (AFS) can generate optimal cocoa bean (BC) yields, produce co-products and provide ecosystem services. This study analyzes the interactions between climate, AFS structure and BC yield in six climatic zones across three natural regions of Colombia. A total of 305 plots of 1,000 m^2 each were established in 132 farms where the cocoa-AFS structure, BC yield and climatic variables were determined. Five typologies of cocoa-AFS were obtained based on the characteristics of the shade canopy and the abundance of cocoa trees: "Highly diversified multistratum with high biomass" (HDMHB), "Diversified multistratum with high shade and abundance of Musaceae (DMHSM)," "Diversified multistratum with high abundance of cocoa trees (DMHDC)," "Diversified monostratum with low shade (DMLS)" and "monostratum with minimal shade (MMS)." In the departments of Huila and Caquetá, Andean and Amazonia regions, respectively, the HDMHB typology predominated, while in Meta, the Orinoquia region, it was MMS. In the temperate-humid zone, the DMHDC and DMHSM typologies were not found. A high floristic diversity of the shade canopy was found: 229 species; Caquetá registered the highest number (152). The most frequent canopy companion species were *Musa paradisiaca*, *Cariniana pyriformis*, *Cedrela odorata*, *Psidium guajava*, *Musa sapientum,* and *Cordia alliodora*. The highest abundance of cocoa trees occurs in areas with lower temperature and relative humidity and in AFS with lower abundance of fruit and timber trees. Zones with higher temperature and lower precipitation had higher abundance of timber species ($r = 0.23$). The BC yield is higher in areas with higher precipitation and is related to the lower abundance of individuals of timber and fruit species, and to the higher abundance of Fabaceae. The BC yield depends on the typology ($p < 0.0001$) of the cacao systems and was higher in DMHDC (1,148 kg ha^{-1} $yr.^{-1}$). These results are key for the design of cocoa-AFS farms that maximize the integral production of BC, co-products and ecosystem services, approaching sustainable cocoa farming.

KEYWORDS

sustainable agriculture, agroforestry systems, ecosystem services, self-consumption, floristic composition

1 Introduction

Agroforestry systems (AFS) are considered as a solution to climate and food security challenges (Reppin et al., 2019; Ballesteros et al., 2022; Koutouleas et al., 2022). The inclusion of several tree species increases biodiversity, productivity and the provision of ecosystem services (Vaast and Somarriba, 2014; Wartenberg et al., 2017; Notaro et al., 2021; Numbisi et al., 2021), improving the well-being of farmers (Vaast and Somarriba, 2014; Hernández-Núñez et al., 2021b; Scudder et al., 2022) by obtaining benefits that are not achieved with monoculture production systems (Maney et al., 2022). The AFS are the association of trees as a shade canopy and a crop adapted to grow under it (Notaro et al., 2021). Their design depends on ecological, productive and local knowledge factors, such as the predominant vegetation, land tenure and decision making (Numbisi et al., 2021). This is the case of cocoa (*Theobroma cacao* L.), which is planted under different levels of shade across approximately 70% of plantations worldwide (Vaast and Somarriba, 2014), where shade is generated by one or more companion species (Deheuvels et al., 2012; Hosseini et al., 2017; Jagoret et al., 2018; Notaro et al., 2021; Schmidt et al., 2022).

The cocoa tree, native to the Amazon region (Motamayor et al., 2002), is one of the most important agricultural crops in tropical regions (Hosseini et al., 2017; Gonas et al., 2022). This production system is the livelihood of approximately five million rural households (Scudder et al., 2022), 80% of which present vulnerable conditions (Vaast and Somarriba, 2014). Cocoa planted under AFS allows multiple benefits, such as: (a) conservation of biodiversity and generation of ecosystem services (Deheuvels et al., 2014; Vaast and Somarriba, 2014; Asigbaase et al., 2019; Maney et al., 2022), (b) adaptive capacity to climate variability and change (Andrade et al., 2013; Salvador et al., 2019; Notaro et al., 2021; Zequeira-Larios et al., 2021; Hernández-Núñez et al., 2021a), (c) contribution to self-consumption, food security and food and nutritional sovereignty (Vaast and Somarriba, 2014; Hosseini et al., 2017; Saj et al., 2017; Asigbaase et al., 2019; Notaro et al., 2021; Gonas et al., 2022), (d) decrease in the economic vulnerability of households (Cerda et al., 2014; Vaast and Somarriba, 2014; Hosseini et al., 2017; Hernández-Nuñez et al., 2020; Notaro et al., 2021; Somarriba et al., 2021; Zequeira-Larios et al., 2021), and (e) synergy that makes the production system sustainable (Vaast and Somarriba, 2014; Hosseini et al., 2017; Wartenberg et al., 2017; Asigbaase et al., 2019; Notaro et al., 2021; Zequeira-Larios et al., 2021; Maney et al., 2022).

Despite the importance of cocoa AFS, their complexity can present difficulties at the production (such as increased incidence of pests and diseases) and technological level (such as pruning and fertilization management) (Correa et al., 2014; Vaast and Somarriba, 2014; Espinosa, 2016), which generate negative impacts on production (Correa et al., 2014; Sterling et al., 2015). These conditions threaten the sustainability of the crop, which has a direct impact on the well-being of rural households (Scudder et al., 2022). Additionally, the improvement of cocoa AFS, setting bean yield as the only criterion, invisibilize the multiple objectives that can be achieved (Vaast and Somarriba, 2014; Hernández-Nuñez et al., 2020), as the other products are as important as cocoa in contributing to household livelihoods (Vaast and Somarriba, 2014; Hosseini et al., 2017).

The design of the AFS must contemplate the physiological needs of the crop (Fedecacao, 2015; Hosseini et al., 2017; Suárez et al., 2018), the challenges and objectives of the rural household (Numbisi et al., 2021; Zequeira-Larios et al., 2021; Rodríguez et al., 2022) and the local biophysical and socioeconomic conditions (Reppin et al., 2019). The interactions of the above factors determine whether there are synergistic or competitive effects in the production system (Notaro et al., 2021). An adequate AFS design can achieve optimal cocoa bean yields, generate co-products and enhance the provision of ecosystem services, aspects that improve household well-being (Hosseini et al., 2017; Asigbaase et al., 2019; Hernández-Nuñez et al., 2020; Numbisi et al., 2021; Zequeira-Larios et al., 2021). Moreover, AFS are not static but change over farm age and production cycles (Numbisi et al., 2021).

This study analyzes the interactions between climatic conditions, shade canopy structure, floristic composition, pest and disease incidence and yield in cocoa production systems in Colombia. The guiding research questions were: How are plant species compositions in cocoa AFS in Colombia? What is the relationship between climatic conditions and shade canopy typologies in cocoa AFS? and How do AFS typologies affect pest and disease incidence and cocoa bean yield? The answers to the questions posed will provide academic inputs for the integrated management of cocoa production systems. Our results aim to find cocoa AFS based on the interaction and balance between a high production of dry cocoa beans and a high generation of companion species that contribute to security, diversify diets and have a greater capacity to adapt to climate change.

2 Materials and methods

2.1 Study area and selected population

The study was conducted in Colombia, in the departments of Huila, Meta and Caquetá, which are in the Andean, Orinoco and Amazon regions, respectively. These departments were taken as representative of the natural regions of greatest importance for cocoa cultivation. Sixteen municipalities in the three departments were selected based on their agro-climatic conditions and the participation of cocoa cultivation in the productive dynamics of the region, considering: (a) area planted, (b) bean yield, (c) marketing or processing, and (d) presence of cocoa organizations.

A total of 305 sample plots were selected in 132 cocoa producing farms (22, 51 and 59 in Meta, Huila and Caquetá, respectively) registered in the Cooperativa Agroindustrial de Cacaoteros del Meta -CACAOMET-, the Red de Asociaciones de Productores de Cacao del Huila -APROCAHUILA- and the Asociación Departamental de Cultivadores de Cacao y Especies Maderables del Caquetá -ACAMAFRUT-. The producers were randomly selected, proportionally to the total number in each department. Visits were made to the producers' farms to identify cocoa plots under AFS, in which an area 1,000 m^2 (50 × 20 m) was established in each plot, corresponding to 83, 100, and 122 in Meta, Huila and Caquetá, respectively (Jagoret et al., 2017; Suárez et al., 2018; Hernández-Nuñez et al., 2020). According to the Caldas Lang climate zone classification, 157 of these plots were located in the Humid Warm zone, 22 in Semi-Arid Warm, 31 in Semi-Humid Warm zone, 11 in Humid Temperate zone, 51 in Semi-Arid Temperate and 33 in Semi-Humid Temperate zone (supplementary) (Ideam, 2017).

2.2 Tree structure and floristic composition of cocoa production systems

In each plot, the position of each individual was projected on a Cartesian plane with respect to the south-west corner of the plot (Suárez et al., 2018; Hernández-Nuñez et al., 2020) and different dasometric measurements were taken: (a) trunk diameter at breast height (dbh); (b) mean crown diameter and; (c) height – total and at the base of the crown (Arango-Ulloa et al., 2009; Ngo Bieng et al., 2013). Only companion trees with dbh ≥ 2.5 cm were measured. In the case of cocoa and coffee trees, trunk diameter was measured at 50 and 15 cm height, respectively (Hernández-Núñez et al., 2021a). Botanical samples of the companion trees were taken for identification to species level at the *Laboratorio de Malherbología y Agrobiodiversidad de la Universidad de la Amazonia*. The companion species were classified according to their use as food, palms, legumes, timber, Musaceae and others. From this information, 74 variables were estimated, grouped into seven components: (1) shade; (2) height; and (3) the selection of variables was based on work by Ngo Bieng et al. (2013), Jagoret et al. (2017), Suárez et al. (2018), and Hernández-Nuñez et al. (2020).

2.3 Climatic conditions

The geographic position of the center of each sample plot was determined using a Global Positioning System with an accuracy of 3 m. For each plot, annual climatic information was obtained for a 20-year period (2000–2020) for the following variables: (a) mean temperature (°C), (b) relative humidity (%), and (c) precipitation (mm). This information was downloaded from "The POWER Project," which provides solar and meteorological data sets from the National Aeronautics and Space Administration-NASA research (Sparks, 2018). The download was performed using the "nasapower" library in the R Core Team statistical software (R Core Team, 2021; Sparks, 2021).

2.4 Incidence and severity of pests and diseases in cocoa production systems

In each plot, the infestation and severity of damage caused by the insect *Monalonium dissimulatum* and the fungi *Moniliophthora roreri* and *Phytophthora* spp. were measured. The degree of external severity of *M. roreri* damage was estimated on 50 pods per plot, using the scale used by Sterling et al. (2015): 0, healthy pod; 1, oily spots; 2, swelling and/or premature ripening; 3, spot (necrosis); 4, mycelium up to 25% of the necrotic spot; and 5, mycelium covering more than 25% of the necrotic spot. A longitudinal cut was made on 50 pods to determine internal severity. The percentage of internal necrosis caused by *M. roreri* was measured and ranked from 0 to 5: 0, no necrosis; 1, 1–20%; 2, 21–40%; 3, 41–60%; 4, 61–80%; and 5, more than 80% of with necrosis (Sterling et al., 2015). The incidence of *Phytophthora* spp. and *M. dissimulatum* was determined by counting all the pods of the trees in the plot and identifying those affected (Vargas et al., 2005; Ramírez, 2016). The percentage of incidence was estimated as the ratio between number of affected pobs and numbers of evaluated cobs ×100.

The severity of *Phytophthora* spp. damage was estimated on 50 pods. This was categorized on a grade from 1 to 5: 1, symptom-free; 2, less than 2 mm affected; 3, affected between 2 mm and 2 cm; 4, affected up to 25%; and 5, spots on more than 25% of the pod (Ramírez, 2016). The severity of *M. dissimulatum* was estimated by counting the number of bites on all pods of all cocoa trees per plot. The severity of this affectation was ranked from 0 to 4, as follows: (0) zero stings; (1) 1–10 stings; (2) 11–25 stings; (3) 26–50 stings; (4) more than 50 stings (Vargas et al., 2005).

2.5 Cocoa bean yields

In each plot, 50 mature cobs of the main genotype of the lot were collected and the fresh kernels of each were weighed. Subsequently, grain yield during the peak production period of each department was estimated using the following formula proposed by Jagoret et al. (2017):

$$R = NbPods \times Wbeans \times TC \times KkoDens$$

donde;
R: yield ($kg\,ha^{-1}\,year^{-1}$).
NbPods: average number of pods/cacao tree.
Wbeans: average weight of fresh beans ($kg\,pod^{-1}$).
TC: fresh grain to dry grain conversion ratio.
KkoDens: abundance of cocoa trees (individuals ha^{-1}).

2.6 Data analysis

2.6.1 Typification of tree structure and floristic composition

The types of cocoa agroforestry systems were identified using the variables of the seven components of tree structure and floristic composition and the abundance of cocoa trees. The variables that make up each of the seven components of the cocoa-AFS were transformed to a scale between 0 and 1; based on this, seven indices were generated because of the sum of these transformed variables per component (Supplementary Table S1). With the seven indices and the variable "abundance of cocoa trees," a classification of the plots was generated using a hierarchical cluster analysis, with Ward's method and Euclidean distance (Balzarini et al., 2008).

The influence of the 74 variables of the seven components and the abundance of cocoa trees on the separation of the groups (Cocoa types-AFS) was estimated by an analysis of variance. The continuous variables were analyzed using linear mixed models (MLM), with the typologies as a fixed effect, based on cluster analysis, and the natural regions as a random effect. The model assumptions were evaluated by graphical inspection of the residuals. When heterogeneous variances between typologies were detected, the variance–covariance matrix was modeled (Di Rienzo et al., 2011). Discrete variables were analyzed using generalized linear mixed models (GLMM) with Poisson distribution (Di Rienzo et al., 2017). Fisher's LSD test ($p < 0.05$) was used for mean comparisons. The association of clusters with departments and with climatic zones was performed by contingency table analysis. Relationships between cocoa tree and companion species variables were estimated with Spearman correlation analysis. Multiple relationships between the dasometric measures of companion species and cocoa trees were performed through a Principal Component Analysis (PCA) (Balzarini et al., 2008). The analyses were performed using the statistical software InfoStat (Di Rienzo et al., 2019) and R Core Team (R Core Team, 2021).

2.6.2 Climatic conditions, pests and diseases and dry cocoa bean production in cocoa agroforestry system types

Spearman correlation analysis was performed between climatic variables and component variables describing tree structure and floristic composition (supplementary). A tri-plot using Partial Least Squares Regression (PLS) was performed to order the plots according to the climatic variables (predictors) and the abundance of cocoa trees and accompanying individuals (dependent), identifying the types of cocoa agroforestry systems (Balzarini et al., 2008).

Additionally, an analysis of variance was performed to determine the influence of cocoa AFS types on pest and disease incidence and severity status (using MLGM) and cocoa bean yield (using MLM) with fixed effect of typology and random effect of department (Di Rienzo et al., 2011, 2017). Finally, a linear regression analysis was performed to determine the relationship between cocoa bean yield (response variable) and tree structure, shade and climate variables (independent or predictor variables) (Balzarini et al., 2008).

3 Results

3.1 Types of cocoa production systems in Colombia

The 305 plots were grouped into five types of cocoa agroforestry systems with significant difference ($p < 0.0001$) among them (Supplementary Table S1): Highly diversified multistratum with high biomass (HDMHB), Diversified multistratum with high shade and abundance of Musaceae (DMHSM), Diversified multistratum with high abundance of cocoa trees (DMHDC), Diversified monostratum with low shade (DMLS) and monostratum with minimum shade (MMS).

Highly diversified multistratum with high biomass (HDMHB) (31.2%, *n* = 95). This typology presented a high diversity of companion species (richness = 6.52 species, Shannon Weaver index = 1.43) and the highest diversity in potential uses (richness of 6.45 uses, Shannon Weaver index = 1.6) (Supplementary Table S1). This typology presented on average 788 individuals ha^{-1} of cocoa trees and 211 individuals ha^{-1} of companion species, which are distributed in the low, medium and high strata (64, 34 and 2%, respectively). The 32 and 29% of the companion species correspond to timber species and Musaceae, with 68 and 61 individuals ha^{-1}, respectively. The accompanying individuals presented the largest basal area and dbh in the three strata and in all use categories with a dbh of 36.2 cm. This typology presented a high shade, generated by individuals of companion species (30.5%) (Supplementary Table S1).

Diversified multistratum with high shade and abundant Musaceae (DMHSM) (10.8%, *n* = 33). This typology presented high values of companion species diversity (richness = 6.73 species, Shannon Weaver index = 1.14) and diversity in potential uses (richness = 6 uses, Shannon Weaver index = 1.48 uses). This cacao AFS typology was characterized by having the lowest abundance of cocoa trees (574 individuals ha^{-1}) and the highest abundance of companion species (481 individuals ha^{-1}), most of them in the middle and low strata. These cocoa plantations had a high abundance of timber and moss species (169 individuals ha^{-1} and 140 individuals ha^{-1}, respectively). Despite the high abundance of companion species, the individuals had small diameters (dbh = 12.3 cm). The shade accompanying cocoa in the plots of this typology was 36.8% (Supplementary Table S1).

Diversified multistratum with high abundance of cocoa trees (DMHDC) (15.7%, *n* = 48). This typology presented average values of companion species diversity (richness = 5 species, Shannon Weaver index = 1.2) and a high diversity of potential uses (richness = 6.4 uses, Shannon Weaver index = 1.6). This typology reached the highest abundance of cocoa trees (1,259 individuals ha^{-1}) and 196 individuals ha^{-1} of companion trees. Of the companion trees, 68 and 32% are of low and medium stratum, respectively. A total of 86% of the companion individuals correspond to: Musaceae (42%) with 82 individuals ha^{-1}, timber (25%) with 50 individuals ha^{-1} and food species (19%) with 36 individuals ha^{-1}. It had the largest basal area (13.83 m^2 ha^{-1}). The accompanying shade to cocoa in the plots of this typology was 25%.

Diversified monostratum with Low shade (DMLS) (23.3%, *n* = 71). This typology was characterized by an average abundance of 726 individuals ha^{-1} of cocoa trees, and a low abundance of companion individuals (143 individuals ha^{-1}), with no trees in the upper stratum. The highest percentage of accompanying individuals corresponded to Musaceae (34%), with 48 individuals ha^{-1}. This typology presented a low percentage of shade from companion species (16.9%) (Supplementary Table S1).

Monostratum with minimum shade (MMS) (19.0%, *n* = 58). This typology presented the lowest diversity of companion species (richness = 2.3 species, Shannon Weaver index = 0.57), and potential uses (richness of 4.7 uses, Shannon Weaver index = 1.23 uses). It had an average abundance of 871 individuals ha^{-1} of cocoa trees and was characterized by having the lowest abundance of companion species (90 individuals ha^{-1}) and no individuals in the upper stratum. It also had the lowest shade canopy (5.5%) (Supplementary Table S1).

Using the tree structure and floristic composition indices, the principal component analysis (PCA) explained 63% of the variance of the data with the first two axes. The first component allows sorting the PCAs in order of complexity, with HDMHB being the most complex, followed by DMHSM and DMHDC, then DMLS and finally the simplest, MMS. The abundance of cocoa trees only allows separating DMHSM from the rest. The variables with the strongest contribution to the separation in CP1 are the shade index and the height index. In the case of the indices that have more strength in CP2, the variables with the greatest contribution were the abundance of companion species (associated with DMHSM) and abundance of cocoa, associated with DMLS, DMHDC, HDMHB and MMS (Figure 1A). Significant negative correlations ($p < 0.05$) were found for the abundance, basal

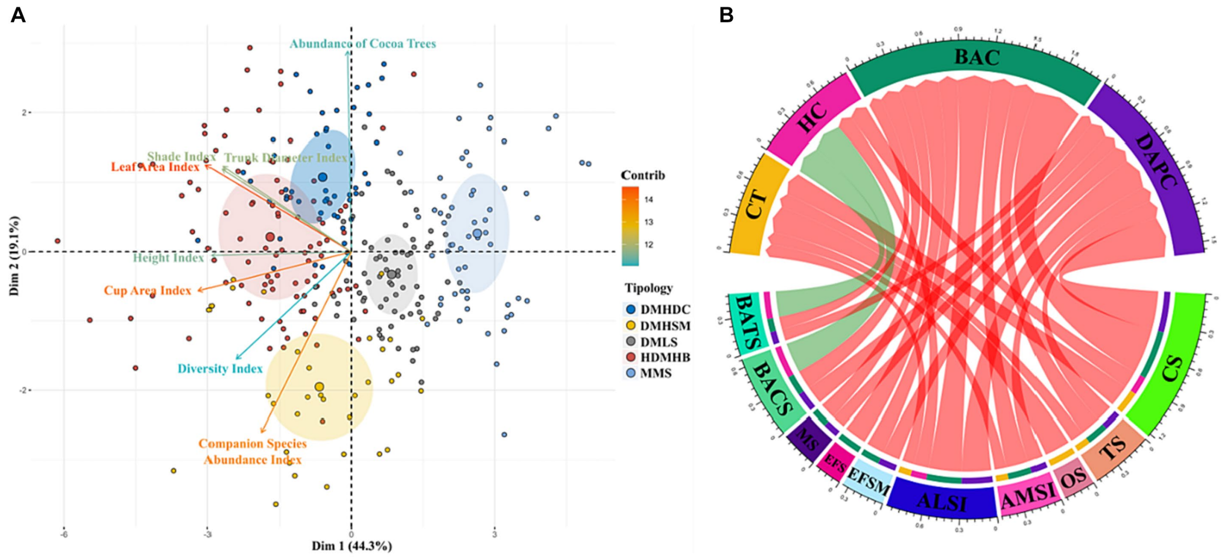

FIGURE 1
Variables of tree structure and floristic composition of cocoa production systems in the departments of Caquetá, Huila and Meta, Colombia. **(A)** Bi-plot constructed by principal component analysis using the component indices of tree structure and floristic composition of cocoa AFS and identifying the AFS types. **(B)** Significant Spearman correlations ($p < 0.05$) between variables of tree structure and floristic composition of cocoa companion species and cocoa trees. Green color: positive correlations; red color: negative correlations; width: strength of correlation. CS, Companion Species; TS, Timber Species; OS, Other Companion Species; AMSI, High stratum individuals; ALSI, Low stratum individuals; BALSS, Basal area of low stratum individuals; EFS, food species; MS, musaceous species; BACS, basal area of companion species; BATS, basal area timber individuals; BAC, basal area cocoa trees; HC, height cocoa trees; Cos, percentage shade cocoa trees; CT, number of cocoa trees; AS, palms; FSE, leguminous plants.

area and shade of cocoa trees with the abundance, basal area and height of companion individuals (Figure 1B).

3.2 Spatial distribution of cocoa production system typologies

The distribution of cocoa production system typologies was heterogeneous among natural regions and climatic zones. In Huila, 86% of the systems corresponded to the typologies: HDMHB (42%), DMHDC (31%), DMLS (13%); while MMS and DMHSM only represented 9 and 5% of the total plots, respectively. In Meta, 75% of the plots corresponded to: MMS (42%) and DMLS (34%), while no HDMHB typology were found (Figure 2). In Caquetá, 68% of the plots were of the HDMHB (43%) and DMLS (25%) typologies; only 3% of the plots corresponded to DMHDC (Figure 2).

In the Humid Temperate zone, no plots of the DMHDC and DMHSM typologies were found; in this same zone, the largest number of plots corresponded to DMLS (45%) and MMS (36%). The HDMHB typology was uniformly presented in the different climatic zones. In the Humid Warm zone, the DMLS typology predominated, followed by HDMHB and MMS with 29, 23 and 22% of plots, respectively. In the Warm Semiarid and Warm Semi-humid zones, most of the plots were of the HDMHB typology with 41 and 55%, respectively. In the Temperate Semiarid zone, the DMHDC and HDMHB typologies were the most abundant (35% each); while the DMHSM and MMS typologies were the least present (4 and 6%, respectively). Finally, in the Semi-humid Temperate zone, the largest number of plots corresponded to HDMHB and MMS with 39 and 30%; while the least common were DMHSM and DMHDC with 3% of plots in each case.

3.3 Floristic diversity of cocoa production systems

A total of 229 species, corresponding to 54 taxonomic families (Figure 3A), were found in 30.5 ha of cocoa plantations in the three departments. Caquetá recorded the highest number of species (152, 66.3% of the total of the study) grouped in 112 genera and 49 families, with dominance of the species *Musa paradisiaca* L., *Cariniana pyriformis* Miers., *Cedrela odorata* L., *Psidium guajava* L., *Musa sapientum* L., and *Cordia alliodora* (Ruíz & Pav.) Oken. In Huila and Meta, a similar number of species (64 and 67), genera (57–52) and taxonomic families (28–25) were found, respectively; with the highest frequency of *Musa paradisiaca* L., *Persea americana* Mill. and *Gliricidia sepium* (Jacq.) Kunth ex Walp. found, while *Musa sapientum* L. was found only in Huila (Figures 3A,B).

Musa paradisiaca L. was the most frequent species in all typologies (48–63% of the plots) (Figure 3B). However, the abundance of Musaceae presented significant differences between typologies ($p < 0.0001$) (Supplementary Table S1), with the highest abundance of *Musa paradisiaca* L. and *Musa sapientum* L. (174 and 142 individuals ha^{-1}, respectively) in DMHSM; in addition, this typology showed a high abundance of *Hevea brasiliensis* (Willd. ex A. Juss.) Müll. Arg. and *Manihot esculenta* Crantz, which are present in 42 and 27% of the plots, respectively (Figures 3A,B). The HDMHB cocoa plantations had the highest number of species (142), with high frequency of *Psidium guajava* L., *Cedrela odorata* L., *Cariniana pyriformis* Miers, *Erythrina poeppigiana* (Walp.) O. F. Cook and *Persea americana* Mill (Figures 3A,B). The MMS typology presented the lowest richness: 23 families, 34 genera and 42 species, where *Musa paradisiaca* L. and *Persea americana* Mill. were in 48 and 29%

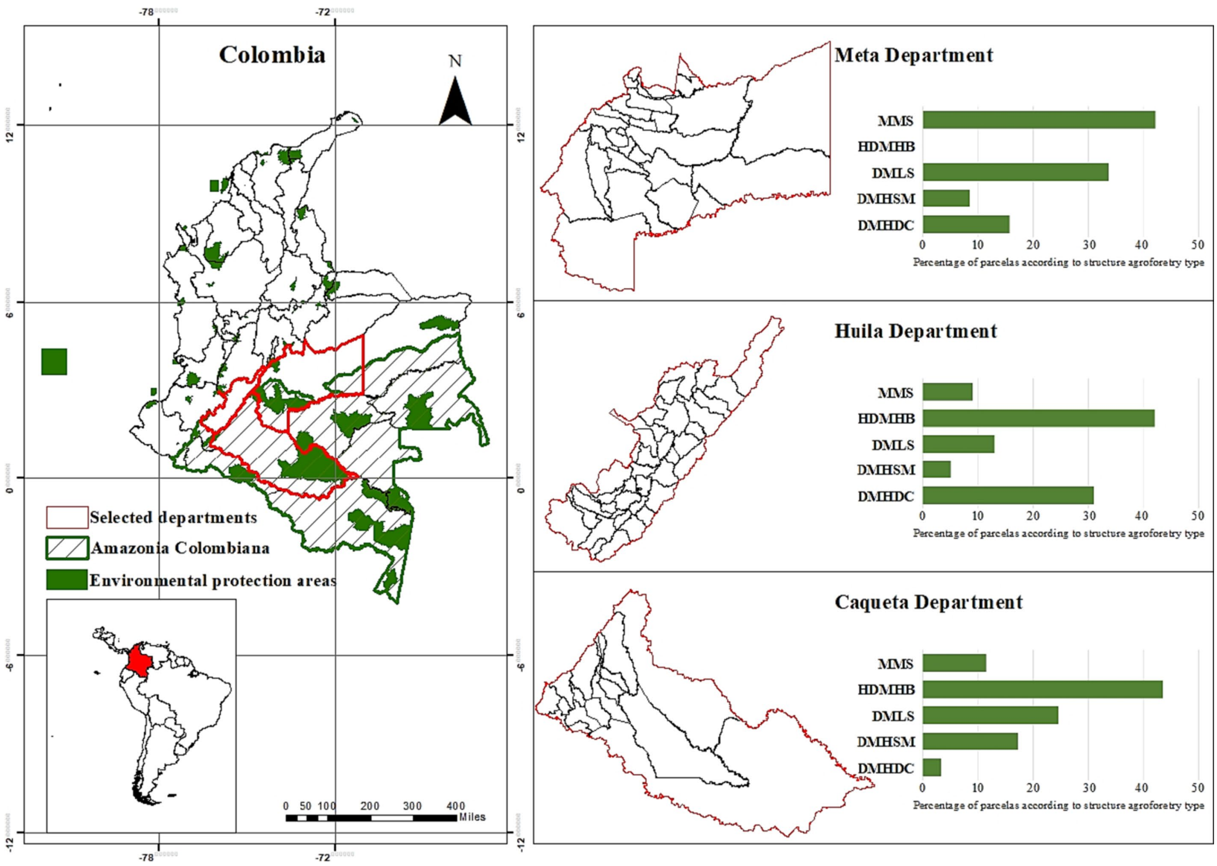

FIGURE 2
Spatial distribution of cocoa crop plots by typology in the departments of Caquetá, Huila and Meta, Colombia. Highly diversified multistratum with high biomass (HDMHB), Diversified multistratum with high shade and abundance of musaceae (DMHSM), Diversified multistratum with high abundance of cocoa trees (DMHDC), Diversified monostratum with low shade (DMLS), and Monostratum with minimum shade (MMS).

of the plots with an abundance of 49 and 68 individuals ha^{-1}, respectively. The highest species richness was reported in humid warm climate zones, with *Musa paradisiaca* L., *Persea americana* Mill., *Gliricidia sepium* (Jacq.) Kunth ex Walp. and *Psidium guajava* L. and *Cedrela odorata* L. being the most frequent (Figures 3A,B). In general, the cocoa plantations hosted a high diversity of companion species, with a maximum of 20 species per plot, with an average of five species.

The shade accompanying the cocoa tree presented negative correlations ($p < 0.05$) with precipitation and relative humidity variables ($r = -0.12$ and -0.18, respectively). Richness and Shannon Weaver index presented positive correlations with temperature ($r = 0.20$ and 0.14, respectively). On the contrary, Shannon Weaver index and diversity of potential uses were significantly ($p < 0.05$) and negatively correlated with relative humidity ($r = -0.20$ and -0.19, respectively) (Figure 4B).

3.4 Relationships between climatic conditions, tree structure and floristic composition

Significant correlations ($p < 0.05$) were found between the variables describing tree structure and climatic conditions (Figure 4B). The highest abundance of cocoa trees occurred in areas where temperature and relative humidity were lower ($r = -0.34$ and -0.18, respectively) (Figure 4B). The correlations between abundance and climatic conditions were different according to the categories of uses of the shade canopy species. For example, in areas of high temperature and low precipitation, a higher abundance of timber species was found ($r = 0.23$) (Figures 4A,B). The abundance of Musaceae was higher in areas with lower relative humidity (Figures 4A,B).

3.5 Relationship between pest and disease attack, bean production, cocoa farm type and climatic conditions

Cocoa bean yield showed statistical differences ($p < 0.0001$) between typologies, where DMHDC had the highest value (1,148 $kg\,ha^{-1}\,yr.^{-1}$). DMHSM had the lowest yield (655 $kg\,ha^{-1}\,yr.^{-1}$), 42.9% lower than DMHDC. The MMS, HDMHB and DMLS typologies reached intermediate yields (855, 806 and 767 $kg\,ha^{-1}\,yr.^{-1}$, respectively) (supplementary). Grain index, pod index, wet to dry grain transformation coefficient and grain weight did not show significant differences ($p > 0.05$) between typologies.

Cocoa bean yield was affected by different conditions of shade canopy, climate and phytosanitary status. In areas with higher rainfall,

FIGURE 3
Floristic diversity of cocoa AFS in the typologies, departments and climatic zones in the departments of Caquetá, Huila and Meta, Colombia. **(A)** Taxonomic richness at family, genus and species level; purple, orange and lilac dots denote the number of families, genera and species, respectively. **(B)** Frequency expressed as percentage of species presence. The colors and sizes of the circles refer to the frequency (0–100%).

cocoa bean yield was higher; the opposite behavior occurred in areas with high incidence of Monilia, and high values of timber trees and Musaceae ($p < 0.05$) (Table 1). Bean yield was negatively affected ($p < 0.05$) by the incidence of Monalonion and Phytophthora ($r = -0.23$ and $r = -0.18$, respectively). Similarly, internal and external severity of Monilia reduced yield ($r = -0.19$ and $r = -0.16$,

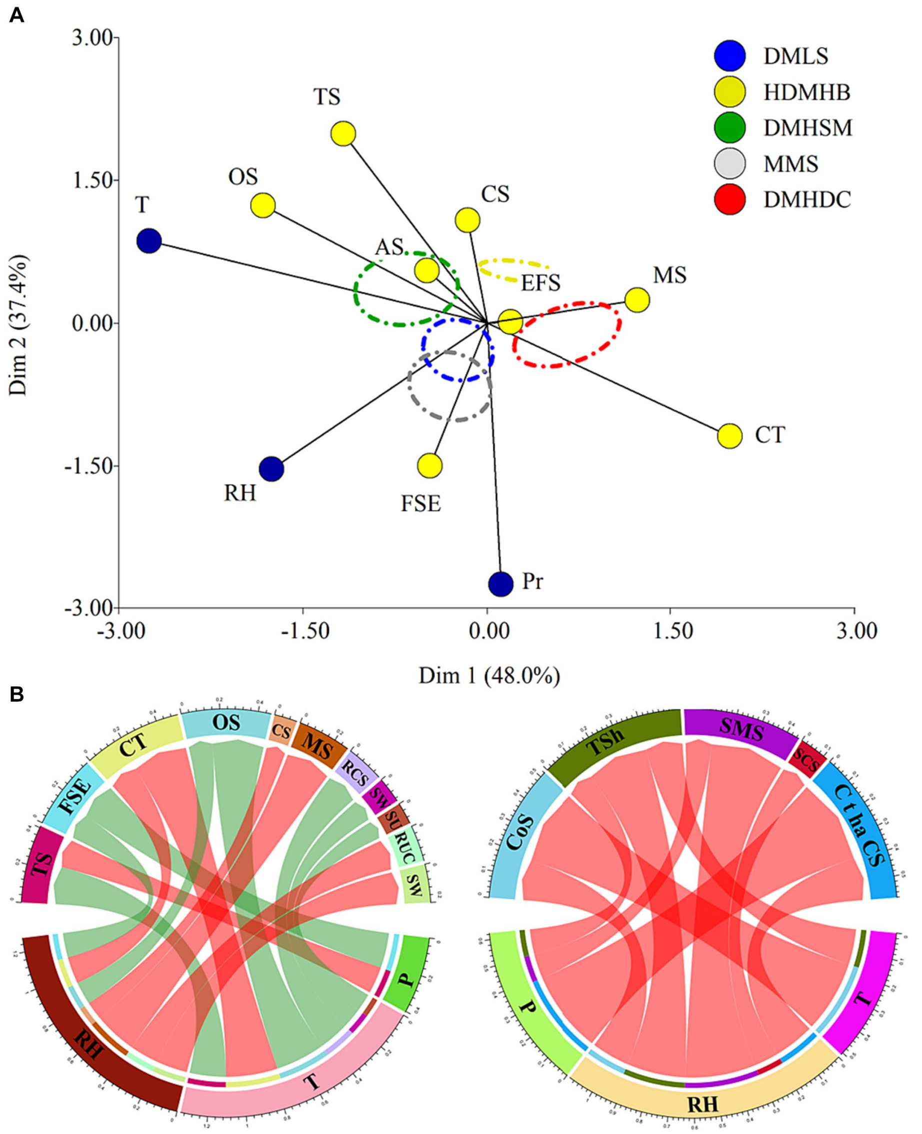

FIGURE 4
Relationships between climatic conditions and tree structure and floristic composition variables in cocoa crops in the departments of Caquetá, Huila and Meta, Colombia. **(A)** Tri-plot constructed by PLS using climatic variables as predictors (blue dots), abundance of cocoa trees and accompanying individuals as dependent (yellow dots) and identifying cocoa production system typologies. **(B)** Significant Pearson correlations ($p < 0.05$) between tree structure variables and floristic composition of cocoa production systems and climatic variables; green color represents positive correlations; red color represents negative correlations; width represents the strength of the correlation. CS, companion species; TS, timber species; OS, other companion species; EFS, food species; MS, Musaceae species; CT, number of cocoa trees; AS, palms; FSE, leguminous plants; T, mean annual temperature; RH, annual relative humidity; P, annual precipitation.

respectively). The abundance of timber, fruit, Musaceae and other species was negatively related ($p < 0.05$) with cocoa yield, while the abundance of Fabaceae was positively correlated ($p < 0.05$) with this variable.

4 Discussion

Cocoa production in Colombia is carried out under different AFS, without an exclusive design by zones. In this regard, Ndo et al. (2023) indicate that the specific diversity leads to a diversity of spatial structures that can be adopted by communities, as a number of species vary greatly from one farm to another. This defines the different production and sustainability approaches that cocoa crops can have, which although, in a general way can be defined as cocoa planted in monoculture or in AFS (Jaimes et al., 2022), the latter has different variations in its design (Suárez et al., 2018; Notaro et al., 2020); where, the number and type of plants are important factors in defining the spatial structure adopted by farmers (Ndo et al., 2023).

In the three areas studied, five types of cocoa plantations were found with differences in their structure and floristic composition (i.e., number and type of species, percentage of shade): Highly diversified multistratum with high biomass (HDMHB), diversified multistratum with high shade and abundance of Musaceae (DMHSM), diversified multistratum with high abundance of cocoa trees (DMHDC), diversified monostratum with low shade (DMLS) and monostratum

TABLE 1 Multiple regression coefficient and univariate correlations between the different variables evaluated and the response variable (dry cocoa bean yield per hectare) in cocoa crops in the departments of Caquetá, Huila and Meta, Colombia.

Variable	Unit	Multiple regression coefficient			Correlations	
		p-value	CpMallows	VIF	Coefficient	*p*-value
Cocoa trees	Individuals ha^{-1}	<0.0001	255.69	1.17	0.63	<0.0001
Cocoa companions		0.01	−12.06	1.12	−0.22	0.0001
Fabaceae		0.01	11.08	1.12	0.15	0.0121
Food species					−0.12	0.0455
Musaceae					−0.12	0.0369
Timber					−0.2	0.0007
Other species companion species					−0.14	0.0201
Cocoa companion wealth	Number species				−0.17	0.0034
Percentage of shade of companion species	%				0.27	<0.0001
Precipitation	mm year	<0.0001	33.35	1.29	0.24	<0.0001
Temperature	°C	<0.0001	18.86	1.29		
Relative humidity	%				0.16	0.01
Monalonium incidence					−0.23	0.0001
Phytophthora incidence		0.03	−10.04	1.08	−0.18	0.0017
External severity of Monilia					−0.16	0.0059
Internal severity Moninilia					−0.19	0.001

with minimum shade (MMS). This has a contradiction with different technical approaches and research, where it is indicated that an adequate plantation should have a certain level of shade and number of species (Fedecacao, 2015). For example, the DMHDC and DMHSM typologies presented, respectively, a higher and lower abundance of cocoa trees than recommended by the technical guidelines of Fedecacao (2015): 600–700 trees ha^{-1}. The first of these typologies was above the average reported in Central America and the second is similar to the average of plantations in Africa (Cerda et al., 2014). Ballesteros et al. (2022) considered the low density of trees (400 individuals ha^{-1}) as one of the disadvantages of the competitiveness of cocoa farms. The abundance of companion species was not uniform between zones either, as high abundance was found in the DMHSM typology with 481 individuals ha^{-1} and low abundance in MMS with 90 individuals ha^{-1}. Research has reported in Ivory Coast, Indonesia, Cameroon, Central American countries and the Colombian Amazon approximately 237, 205, 196, 200, and 127 accompanying individuals ha^{-1}, respectively (Cerda et al., 2014; Suárez et al., 2018). In Africa, they reported 30 accompanying individuals ha^{-1}, corresponding 45 different families, 129 genera and 213 species (Sanial et al., 2023). This is consistent with other research, which has found that the spatial configuration of cocoa trees often deviates from agronomic recommendations (Numbisi et al., 2021).

The dichotomy between the designs of cocoa-based AFS found and the technical recommendations may occur because, as indicated by Lavoie et al. (2023), the design of the AFS does not obey a single factor but is given by the convergence of local conditions (social and environmental), external conditions (projects) and the farmer's own capabilities and projections. For example, farmers are more aware of the multiple uses of cocoa companion species (Zequeira-Larios et al., 2021), which can lead to a higher abundance of these species, as occurs in the DMHSM typology. This reaffirms the potential of cocoa-AFS for multiple production objectives (Vaast and Somarriba, 2014). This behavior goes against the institutional trend of increasing the abundance of cocoa planting, but is in line with the vision of traditional farmers because the low density of cocoa trees allows them to plant diverse crops for their livelihood (Ballesteros et al., 2022). In addition, with appropriate management practices, a balance between bean yield and co-product generation can be achieved (Hernández-Nuñez et al., 2020). For example, the HDMHB typology presented a cocoa bean yield of 855 kg ha^{-1} year^{-1}, which is higher than that reported by different studies (Escobar Ramírez et al., 2021; Gama-Rodrigues et al., 2021; Asitoakor et al., 2022b) and presented an average abundance of 211 accompanying individuals ha^{-1}, mainly of Musaceae, timber species and food generators, which increase the provision of ecosystem services. This is related to what has been suggested by different authors who indicate that the cocoa-AFS can be a socioeconomically and ecologically viable system (Notaro et al., 2021; Gonas et al., 2022), which emphasizes the need to eliminate the bias of studying AFS-cocoa focused on cocoa bean yields without evaluating the complementary economic benefits (Ballesteros et al., 2022).

One factor that agreed with the ranges reported by different authors and technical guides was the percentage of shade, since no typology exceeded 36%. This is in agreement with different authors, who indicate that this should be less than 50% (Zequeira-Larios et al., 2021), where the most recommended is 30%, since a higher shade causes limitations in cocoa bean yield (Ballesteros et al., 2022). However, in departments such as Caquetá, which have fewer daylight hours (3.8 daylight hours day^{-1}), a lower percentage of shade is necessary as reported by Suárez et al. (2018). In this department, there was a higher frequency of the HDMHB typology, which has a high percentage of shade. This can cause a higher incidence of pests and diseases and limit cocoa productivity (Jaimes et al., 2011; Vaast and

Somarriba, 2014; Ortíz et al., 2015; Sterling et al., 2015), which was consistent with the present results, where the higher the percentage of shade, the greater the severity of Monilia.

Research has found different reasons that define the number of companion species to cocoa and the type of species (Salazar-Díaz and Tixier, 2017; Guelly et al., 2021) and is that the diversity of crop species generates a diversity of phenological, morphological and physiological characteristics, whose combination influences the agroecological functioning of FFS through facilitation or competition effects (Notaro et al., 2022). One factor of importance when establishing companion species is to regulate shade for cocoa, as it directly influences the agronomic yield of cocoa beans (Ngo Bieng et al., 2013; Jagoret et al., 2017; Wartenberg et al., 2017; Asare et al., 2018; Suárez et al., 2018). In some cases, farmers have found it necessary to remove forest tree species to achieve high grain yields (Anglaaere et al., 2011). This is due to a trade-off between yields and biodiversity within cropping systems (Notaro et al., 2022). However, authors such as (Trebissou et al., 2021), indicate that competition between trees occurs from the early years in cocoa plantations. Also, Hernández-Nuñez et al. (2020) concluded that proper management of companion species can generate high cocoa bean yields and different environmental and economic services.

Defining the percentage of shade for cocoa is accompanied by different reasons that the producer may have to determine the type of species and amount to plant. Among them, the various environmental, economic and food security services they can generate (Vaast and Somarriba, 2014). Some of these are the improvement of soil conditions (Anglaaere et al., 2011), biodiversity conservation and generation of ecosystem services (Deheuvels et al., 2014; Vaast and Somarriba, 2014; Asigbaase et al., 2019; Maney et al., 2022), adaptive capacity to climate variability and change (Andrade et al., 2013; Salvador et al., 2019; Notaro et al., 2021; Zequeira-Larios et al., 2021; Hernández-Núñez et al., 2021a), food production that diversify the diet and economic income of farmers (Vaast and Somarriba, 2014). Although environmental services are of global interest, Sanial et al. (2023) indicate that there are socioeconomic variables that are more determinant than environmental variables in making decisions on the association of trees to cocoa.

In our study, the typologies in Caquetá recorded a high number of companion species with potential timber and other uses. In some of these cases, this occurs because cocoa planting projects incorporate timber species as companion species (Rodríguez et al., 2022). In other cases, it may be due to the fact that the planting was generated in areas of natural regeneration, where cocoa replaces one of the strata and the upper strata are kept as shade (Jaimes et al., 2022). This is an important practice, as it reduces establishment and maintenance costs (Rodríguez et al., 2022). Furthermore, retained trees provide shade for cocoa and leaf mulch from shade trees and nutrients stored in the forest ground ensure productivity (Hosseini et al., 2017; Asigbaase et al., 2019; Côte et al., 2022). Additionally, these trees enable biodiversity conservation (Vaast and Somarriba, 2014), carbon sequestration (Hernández-Núñez et al., 2021a) and enhance better connectivity, which allows the movement of forest species between remnant patches of primary forest in a wider matrix than open land cocoa-AFS (Maney et al., 2022). These aspects are of high importance in departments such as Caquetá, which belong to the Amazon, but have high deforestation rates (Capdevilla et al., 2023).

Timber trees also diversify household income. In studies by Notaro et al. (2021) and Gonas et al. (2022) the species with high abundance were *Cordia alliodora* (Ruíz & Pav.) Oken, a species that also appears with high frequency in the plots of our study along with *Cedrella odorata* L. Authors such as Reppin et al. (2019), report the importance of other forest species for household provisioning services, such as construction and firewood. In the present investigation, this type of species has high frequency, mainly in the DMHSM typology. Hernández-Núñez et al. (2021a) report that these species also represent an important accumulation of carbon, which contributes to climate change mitigation.

The DMHDC and DMLS cocoa AFS present a high number of mosaic and fruit species, with high abundance and frequency of Musaceae and *Persea americana* Mill species, which are in agreement with global trends reported by different authors (Cerda et al., 2014; Deheuvels et al., 2014; Gonas et al., 2022; Asitoakor et al., 2022a; Ndo et al., 2023). In studies in the Peruvian Amazon, the species with the highest abundance was Musaceae (316 individuals in total) (Gonas et al., 2022); in cocoa crops in Ghana, *Persea americana* was the most common shade tree species (Asitoakor et al., 2022a). In research in Cameroon, fruit trees belonging to different families and species are one of the key components of cocoa-AFS in humid forest areas, accounting for up to 80% of the agrobiodiversity (Ndo et al., 2023). These types of companion species have a high potential for commercialization (Notaro et al., 2021), which diversifies household income sources (Asitoakor et al., 2022a; Jaimes et al., 2022). In addition, they provide food for household consumption, resulting in savings in household expenses (Hosseini et al., 2017). Also, they are shade generators for cocoa (Gonas et al., 2022), which also increases soil fertility by providing organic matter (Notaro et al., 2021).

This trend towards the predominance of fruit and timber trees may indicate that it would be advantageous to plant more citrus or other fruit trees and decrease cocoa trees (Notaro et al., 2021). This may be an indication of the deliberate transformation of the landscape by farmers from natural pioneer species traditionally grown with cocoa to species that provide food and medicinal benefits (Zequeira-Larios et al., 2021; Gonas et al., 2022). Concordant with these statements, the results of this research indicate that there is a negative correlation between cocoa tree abundance and companion species, mainly fruit and timber species. Zequeira-Larios et al. (2021) found in two communities in Mexico differences between the densities of cocoa trees and companion species, indicating that in one community (Tabasco) farmers are more focused on selling cocoa; in this way they keep cocoa trees in constant renewal and maintain shade trees and in (Chiapas), farmers in Chiapas obtain income from cocoa and fruit trees.

Under this scenario and despite the benefits that different authors have raised about companion trees (Andrade et al., 2013; Cerda et al., 2014; Deheuvels et al., 2014; Vaast and Somarriba, 2014; Hosseini et al., 2017; Saj et al., 2017; Wartenberg et al., 2017; Salvador et al., 2019; Hernández-Nuñez et al., 2020; Somarriba et al., 2021; Hernández-Núñez et al., 2021a; Maney et al., 2022), there is a need for proper practices on these trees in the design of cocoa-AFS (Gonas et al., 2022). This is due to factors such as the difficulty and time needed to harvest these trees, the higher space requirements of these species compared to cocoa trees, the sale of some fruit crops is sometimes not possible due to the lack of commercial contacts, which reduces the economic value of these associated species (Notaro et al., 2021), nutrient competition or negative allelopathic effects for cocoa (Jaimes et al., 2022). Finally, this trend of simplification within cocoa agroforests leads to the creation of agrochemical-dependent cocoa systems, called conventional cocoa systems, which smallholder farmers cannot manage due to high input costs (Asigbaase et al., 2019). This has reached extreme consequences, such as the removal of shade trees on their farms due to perceived competition for light, water and nutrients (Asitoakor et al., 2022b), demonstrating that there is a lack of coordinated definition and implementation of cocoa-based AFS, causing sustainable harvesting to be missed (Esche et al., 2022).

5 Conclusion

In Colombia there are five types of agroforestry designs based on cocoa according to the components of the tree structure, floristic composition and the abundance of cocoa trees. We found AFS Highly diversified multistratum with high biomass, diversified multistratum with high shade and abundance of Musaceae, diversified multistratum with high abundance of cocoa trees, diversified monostratum with low shade and monostratum with minimal shade. The most frequent typology was Highly diversified multistratum with high biomass, with an average of 788 individuals ha^{-1} of cocoa trees and 211 individuals ha^{-1} of companion species.

A total of 229 plant species were found within the cocoa-AFS in the area studied. The department of Caquetá, located in the Colombian Amazon, registered the highest number of companion species (66.3% of the total of the study) with a dominance of *Musa paradisiaca* L., *Cariniana pyriformis* Miers., *Cedrela odorata* L., *Psidium guajava* L., *Musa sapientum* L. and *Cordia alliodora* (Ruíz & Pav.) Oken. In Huila and Meta, a similar number of species was found (64 and 67 species); with the highest frequency of *Musa paradisiaca* L., *Persea americana* Mill. and *Gliricidia sepium* (Jacq.) Kunth ex Walp; *Musa sapientum* L. was found only in Huila. In all typologies Musa paradisiaca L. was the most frequent species (48 to 63% of the plots); however, its abundance differed among typologies.

Relationships were found between the components of tree structure, floristic composition and abundance of cocoa trees and climatic conditions. The highest abundance of cocoa trees was found in areas where temperature and relative humidity were lower. In areas of high temperature and low precipitation, a greater abundance of timber species was found, and the abundance of Musaceae was higher in areas with lower relative humidity. The Shannon Weaver index and the diversity of potential uses were negatively correlated with relative humidity.

Cocoa bean yields differed between typologies, with DMHDC and DMHSM having the highest (1,148 kg ha^{-1} $yr.^{-1}$) and lowest (655 kg ha^{-1} $yr.^{-1}$) values. The results allow us to conclude that cocoa bean yield was affected by different conditions of shade canopy, climate and phytosanitary status. In areas with higher rainfall, cocoa bean yield was higher; the opposite behavior occurred in areas with high incidence of Monilia, and high values of timber trees and Musaceae. It was found that the abundance of timber trees, fruit trees, Musaceae and other species was negatively related to cocoa yield, while the abundance of Fabaceae was positively correlated with this variable. The HDMHB typology, which presented a cocoa bean yield of 855 kg ha-1 year-1, higher than reported by different studies, an average abundance of companion species ha-1, mainly Musaceae, timber species and food generators, is a typology that allows to have significant income from cocoa beans and also allows a good provision of ecosystem services, contributions to food security and diversification of economic income, which can partially conclude that it is a typology with high potential to promote in future cocoa farms. However, it is important to solve future research questions that will help to make decisions based on data that integrate more components, such as what is the income derived from the companion species, what is the contribution of companion species to food and nutritional security of households, and what is the contribution of companion species to the food and nutritional security of households?

Finally, we conclude that these typologies have differentiated conditions of cocoa bean production and co-product generation. We found typologies in which there is a high diversity of companion species that generate different ecosystem services and have a high cocoa bean yield. These typologies are important because they become efficient production systems, contributing significantly to the well-being of the rural household by promoting food security, conservation of diversity, generation of extra income and adaptation and mitigation of climate change; aspects that are considered as challenges within the dynamics of the new rurality in Colombia. On the contrary, we found typologies that, although they have a high abundance of companion species, these are generally of natural regeneration processes and do not represent a current or potential use for households and, in addition, have low cocoa yields. These types of production systems can have a demotivating effect on rural producers. However, the design of the AFS is not the only factor that affects bean yield and the generation of co-products, therefore, new research questions arise, such as: What is the relationship between the social conditions of rural households and the agronomic conditions of the crop?

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

HH-N: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Writing – original draft, Writing – review & editing. JS: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. HA: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft, Writing – review & editing. JA: Conceptualization, Data curation, Methodology, Writing – original draft. RN: Conceptualization, Data curation, Methodology, Writing – original draft. DG: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft. GG: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft. IG-M: Conceptualization, Formal analysis, Methodology, Writing – review & editing. FC: Conceptualization, Data curation, Formal analysis, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1295992/full#supplementary-material

References

Andrade, H., Figueroa, J., and Silva, D. (2013). Almacenamiento de carbono en cacaotales (*Theobroma cacao*) en armero-guayabal (Tolima, Colombia). *Sci. Agroalimentaria* 1, 6–10.

Anglaaere, L. C. N., Cobbina, J., Sinclair, F. L., and Mcdonald, M. A. (2011). The effect of land use systems on tree diversity: farmer preference and species composition of cocoa-based agroecosystems in Ghana. *Agrofor. Syst.* 81, 249–265. doi: 10.1007/s10457-010-9366-z

Arango-Ulloa, J., Bohorquez, A., Duque, M. C., and Maass, B. L. (2009). Diversity of the calabash tree (*Crescentia cujete* L.) in Colombia. *Agrofor. Syst.* 76, 543–553. doi: 10.1007/s10457-009-9207-0

Asare, R., Markussen, B., Asare, R. A., Anim-Kwapong, G., and Ræbild, A. (2018). On-farm cocoa yields increase with canopy cover of shade trees in two agro-ecological zones in Ghana. *Clim. Dev.* 11, 435–445. doi: 10.1080/17565529.2018.1442805

Asigbaase, M., Sjogersten, S., Lomax, B. H., and Dawoe, E. (2019). Tree diversity and its ecological importance value in organic and conventional cocoa agroforests in Ghana. *PLoS One* 14:e0210557. doi: 10.1371/journal.pone.0210557

Asitoakor, B. K., Asare, R., Ræbild, A., Ravn, H. P., Eziah, V. Y., Owusu, K., et al. (2022a). Influences of climate variability on cocoa health and productivity in agroforestry systems in Ghana. *Agric. For. Meteorol.* 327:109199. doi: 10.1016/j.agrformet.2022.109199

Asitoakor, B. K., Vaast, P., Ræbild, A., Ravn, H. P., Eziah, V. Y., Owusu, K., et al. (2022b). Selected shade tree species improved cocoa yields in low-input agroforestry systems in Ghana. *Agric. Syst.* 202:103476. doi: 10.1016/j.agsy.2022.103476

Ballesteros, W., Valencia, J. C., and Navia-Estrada, J. F. (2022). Assessment of a cocoa-based agroforestry system in the southwest of Colombia. *Sustain. For.* 14, 1–17. doi: 10.3390/su14159447

Balzarini, M. G., Gonzalez, L., Tablada, M., Casanoves, F., Di Rienzo, J. A., and Robledo, C. W. (2008). *InfoStat*. Córdoba, Argentina: Manual del Usuario.

Capdevilla, D. A. G., Bermúdez, O. B., and Aguirre, M. A. (2023). Alternativas Comunitarias a los Procesos de Deforestación en la Amazonía Colombiana. Caso el Caraño, Caquetá. *Historia Ambiental Latinoamericana Caribeña Revista Solcha* 13, 19–52. doi: 10.32991/2237-2717.2023v13i1.p19-52

Cerda, R., Deheuvels, O., Calvache, D., Niehaus, L., Saenz, Y., Kent, J., et al. (2014). Contribution of cocoa agroforestry systems to family income and domestic consumption: looking toward intensification. *Agrofor. Syst.* 88, 957–981. doi: 10.1007/s10457-014-9691-8

Correa, J., Castro, S., and Coy, J. (2014). Estado de la Moniliasis del cacao causada por Moniliophthora roreri en Colombia. *Acta Agronóm.* 63, 388–399. doi: 10.15446/acag.v63n4.42747

Côte, F. X., Rapidel, B., Sourisseau, J. M., Affholder, F., Andrieu, N., Bessou, C., et al. (2022). Levers for the agroecological transition of tropical agriculture. *Agron. Sustain. Dev.* 42, 1–11. doi: 10.1007/s13593-022-00799-z

Deheuvels, O., Avelino, J., Somarriba, E., and Malezieux, E. (2012). Vegetation structure and productivity in cocoa-based agroforestry systems in Talamanca, Costa Rica. *Agric. Ecosyst. Environ.* 149, 181–188. doi: 10.1016/j.agee.2011.03.003

Deheuvels, O., Rousseau, G. X., Soto Quiroga, G., Decker Franco, M., Cerda, R., Vílchez Mendoza, S. J., et al. (2014). Biodiversity is affected by changes in management intensity of cocoa-based agroforests. *Agrofor. Syst.* 88, 1081–1099. doi: 10.1007/s10457-014-9710-9

Di Rienzo, J., Casanoves, F., Balzarini, M., Gonzalez, L., Tablada, M., and Robledo, C. (2019). *Infostat versión 2019*. Córdoba, Argentina: Universidad Nacional de Córdoba

Di Rienzo, J., Macchiavelli, R., and Casanoves, F. (2011). *Modelos lineales mixtos: aplicaciones en InfoStat. 1st* Córdoba: Grupo InfoStat, 193

Di Rienzo, J.A., Macchiavelli, R.E., and Casanoves, F. (2017). *Modelos lineales generalizados mixtos: aplicaciones en InfoStat*.

Esche, L., Schneider, M., Milz, J., and Armengot, L. (2022). The role of shade tree pruning in cocoa agroforestry systems: agronomic and economic benefits. *Agrofor. Syst.* 97, 175–185. doi: 10.1007/s10457-022-00796-x

Escobar Ramírez, C. H., Córdoba-Gaona, Ó. D. J., Correa Londoño, G. A., and Martínez Bustamante, E. G. (2021). Yield of cocoa under different agroforestry systems in a dry tropical forest in western Colombia. *Bioagro* 34, 39–50. doi: 10.51372/bioagro341.4

Espinosa, J. A. (2016). *Características estructurales y funcionales de un faro agroecológico a partir de las experiencias de productores cacaoteros de las regiones de los departamentos de Nariño, Meta, Caquetá y Tolima Doctorado en Agroecología Tesis de* Doctorado, Universidad de Antioquia.

Fedecacao (2015). *Guía técnica para el cultivo del Cacao*. Bogotá: Federación Nacional de Cacaoteros.

Gama-Rodrigues, A. C., Müller, M. W., Gama-Rodrigues, E. F., and Mendes, F. A. T. (2021). Cacao-based agroforestry systems in the Atlantic Forest and Amazon biomes: an ecoregional analysis of land use. *Agric. Syst.* 194:103270. doi: 10.1016/j.agsy.2021.103270

Gonas, M., Rubio, K. B., Rojas Briceno, N. B., Pariente-Mondragon, E., and Oliva-Cruz, M. (2022). Tree diversity in agroforestry systems of native fine-aroma cacao, Amazonas, Peru. *PLoS One* 17:e0275994. doi: 10.1371/journal.pone.0275994

Guelly, K. A., Pereki, H., and Djiwa, O. (2021). Perceptions ethnoculturelles des services écosystémiques rendus par les agroforêts à base de cacaoyer au Togo. *Base*. 25, 208–222. doi: 10.25518/1780-4507.19153

Hernández-Núñez, H. E., Andrade Castañeda, H. J., Suárez, J. C., Gutiérrez, D., Gutiérrez García, G. A., Trujillo, E., et al. (2021a). Almacenamiento de carbono en sistemas agroforestales en los Llanos Orientales de Colombia. *Biol. Trop.* 69, 352–368. doi: 10.15517/rbt.v69i1.42959

Hernández-Núñez, H. E., Gutiérrez-Montes, I., Bernal-Núñez, A. P., Gutiérrez-García, G. A., Suárez, J. C., Casanoves, F., et al. (2021b). Cacao cultivation as a livelihood strategy: contributions to the well-being of Colombian rural households. *Agric. Hum. Values* 39, 201–216. doi: 10.1007/s10460-021-10240-y

Hernández-Nuñez, H. E., Gutiérrez-Montes, I., Gutiérrez, G. A., Sánchez, J., Suárez, J. C., and Casanoves, F. (2020). Agronomic state of cacao cultivation: its relationship with the capitals endowment of the Colombian rural households. *Agrofor. Syst.* 94, 2367–2380. doi: 10.1007/s10457-020-00556-9

Hosseini, S., Trueman, S. J., Nevenimo, T., Hannet, G., Bapiwai, P., Poienou, M., et al. (2017). Effects of shade-tree species and spacing on soil and leaf nutrient concentrations in cocoa plantations at 8 years after establishment. *Agric. Ecosyst. Environ.* 246, 134–143. doi: 10.1016/j.agee.2017.06.003

Ideam (2017). *Atlas climatológico de Colombia*. Bogotá: Instituto de Hidrología, Meteorología y Estudios Ambientales - IDEAM.

Jagoret, P., Michel, I., Ngnogué, H. T., Lachenaud, P., Snoeck, D., and Malézieux, E. (2017). Structural characteristics determine productivity in complex cocoa agroforestry systems. *Agron. Sustain. Dev.* 37, 1–12. doi: 10.1007/s13593-017-0468-0

Jagoret, P., Ngnogue, H. T., Malézieux, E., and Michel, I. (2018). Trajectories of cocoa agroforests and their drivers over time: lessons from the Cameroonian experience. *Eur. J. Agron.* 101, 183–192. doi: 10.1016/j.eja.2018.09.007

Jaimes, Y., Aránzazu, F., Rodríguez, E., and Martínez, N. (2011). Behavior of introduced regional clones of *Theobroma cacao* toward the infection *Moniliophthora roreri* in three different regions of Colombia. *Agronomia Colombiana* 2, 171–178.

Jaimes, Y. Y., Carvajal-Rivera, A. S., Galvis-Neira, D. A., Carvalho, F. E. L., and Rojas-Molina, J. (2022). Cacao agroforestry systems beyond the stigmas: biotic and abiotic stress incidence impact. *Front. Plant Sci.* 13:921469. doi: 10.3389/fpls.2022.921469

Koutouleas, A., Sarzynski, T., Bordeaux, M., Bosselmann, A. S., Campa, C., Etienne, H., et al. (2022). Shaded-coffee: a nature-based strategy for coffee production under climate change? A review. *Front. Sustain. Food Syst.* 6:877476. doi: 10.3389/fsufs.2022.877476

Lavoie, A., Thomas, E., and Olivier, A. (2023). Local working collections as the foundation for an integrated conservation of *Theobroma cacao* L. in Latin America. *Front. Ecol. Evol.* 10:10. doi: 10.3389/fevo.2022.1063266

Maney, C., Sassen, M., and Hill, S. L. L. (2022). Modelling biodiversity responses to land use in areas of cocoa cultivation. *Agric. Ecosyst. Environ.* 324:107712. doi: 10.1016/j.agee.2021.107712

Motamayor, J. C., Risterucci, A. M., Lopez, P. A., Ortiz, C. F., Moreno, A., and Lanaud, C. (2002). Cacao domestication I: the origin of the cacao cultivated by the Mayas. *Heredity (Edinb)* 89, 380–386. doi: 10.1038/sj.hdy.6800156

Ndo, E. G. D., Akoutou Mvondo, E., Bidzanga Nomo, L., Bella Manga, F., Ambang, Z., and Cilas, C. (2023). Farmer's strategies in the choice of citrus spatial structures in cocoa-based agroforests in Cameroon. *Agrofor. Syst.* 97, 659–672. doi: 10.1007/s10457-023-00817-3

Ngo Bieng, M. A., Gidoin, C., Avelino, J., Cilas, C., Deheuvels, O., and Wery, J. (2013). Diversity and spatial clustering of shade trees affect cacao yield and pathogen pressure in Costa Rican agroforests. *Basic Appl. Ecol.* 14, 329–336. doi: 10.1016/j.baae.2013.03.003

Notaro, M., Collado, C., Depas, J. K., Dumovil, D., Denis, A. J., Deheuvels, O., et al. (2021). The spatial distribution and height of associated crops influence cocoa tree productivity in complex agroforestry systems. *Agron. Sustain. Dev.* 41, 1–14. doi: 10.1007/s13593-021-00716-w

Notaro, M., Deheuvels, O., and Gary, C. (2022). Participative design of the spatial and temporal development of improved cocoa agroforestry systems for yield and biodiversity. *Eur. J. Agron.* 132:126395. doi: 10.1016/j.eja.2021.126395

Notaro, M., Gary, C., and Deheuvels, O. (2020). Plant diversity and density in cocoa-based agroforestry systems: how farmers' income is affected in the Dominican Republic. *Agrofor. Syst.* 94, 1071–1084. doi: 10.1007/s10457-019-00472-7

Numbisi, F. N., Alemagi, D., Degrande, A., and Van Coillie, F. (2021). Farm rejuvenation-induced changes in tree spatial pattern and live biomass species of cocoa agroforests in Central Cameroon: insights for tree conservation incentives in cocoa landscapes. *Sustain. For.* 13, 1–22. doi: 10.3390/su13158483

Ortíz, C., Torres, M., and Hernández, S. (2015). Comparación de dos sistemas de manejo del cultivo del cacao, en presencia de Moniliophthora roreri, en México. *Rev. Fitotec. Mex.* 38, 191–196. doi: 10.35196/rfm.2015.2.191

R Core Team (2021). R: A language and environment for statistical computing. Vienna, Austria. Available at: https://www.R-project.org/

Ramírez, J. (2016). Pérdidas económicas asociadas a la pudrición de la mazorca del cacao causada por Phytophthora spp.,y Moniliophthora roreri (Cif y Par) Evans et al., en la hacienda Theobroma, Colombia. *Revist. Protec. Vegetal.* 31, 42–49.

Reppin, S., Kuyah, S., De Neergaard, A., Oelofse, M., and Rosenstock, T. S. (2019). Contribution of agroforestry to climate change mitigation and livelihoods in Western Kenya. *Agrofor. Syst.* 94, 203–220. doi: 10.1007/s10457-019-00383-7

Rodríguez, T., Bonatti, M., Löhr, K., Lana, M., Del Río, M., and Sieber, S. (2022). Analyzing influencing factors to scale up agroforestry systems in Colombia: a comparative ex-ante assessment of cacao farming and cattle ranching in two regions. *Agrofor. Syst.* 96, 435–446. doi: 10.1007/s10457-022-00730-1

Saj, S., Durot, C., Mvondo Sakouma, K., Tayo Gamo, K., and Avana-Tientcheu, M. L. (2017). Contribution of associated trees to long-term species conservation, carbon storage and sustainability: a functional analysis of tree communities in cacao plantations of Central Cameroon. *Int. J. Agric. Sustain.* 15, 282–302. doi: 10.1080/14735903.2017.1311764

Salazar-Díaz, R., and Tixier, P. (2017). Effect of plant diversity on income generated by agroforestry systems in Talamanca, Costa Rica. *Agrofor. Syst.* 93, 571–580. doi: 10.1007/s10457-017-0151-0

Salvador, P., Cámara, L. D. C., Martínez, J. L., Sánchez, R., and Valdés, E. (2019). Diversidad, estructura y carbono de la vegetación arbórea en sistemas agroforestales de cacao. *Madera Bosques* 25, 1–14. doi: 10.21829/myb.2019.2511638

Sanial, E., Ruf, F., Louppe, D., Mietton, M., and Hérault, B. (2023). Local farmers shape ecosystem service provisioning in west African cocoa agroforests. *Agrofor. Syst.* 97, 401–414. doi: 10.1007/s10457-021-00723-6

Schmidt, J. E., Firl, A., Hamran, H., Imaniar, N. I., Crow, T. M., and Forbes, S. J. (2022). Impacts of shade trees on the adjacent cacao rhizosphere in a young diversified agroforestry system. *Agronomy* 12, 1–16. doi: 10.3390/agronomy12010195

Scudder, M., Wampe, N., Waviki, Z., Applegate, G., and Herbohn, J. (2022). Smallholder cocoa agroforestry systems; is increased yield worth the labour and capital inputs? *Agric. Syst.* 196:103350. doi: 10.1016/j.agsy.2021.103350

Somarriba, E., Peguero, F., Cerda, R., Orozco-Aguilar, L., López-Sampson, A., Leandro-Muñoz, M. E., et al. (2021). Rehabilitation and renovation of cocoa (*Theobroma cacao* L.) agroforestry systems. *Agron. Sustain. Develop.* 41, 1–19. doi: 10.1007/s13593-021-00717-9

Sparks, A. (2018). Nasapower: a NASA POWER global meteorology, surface solar energy and climatology data client for R. *J. Open Source Soft.* 3:1035. doi: 10.21105/joss.01035

Sparks, A. (2021). Nasapower: NASA-POWER data from R. R package version 4.0.0. Available at: https://CRAN.R-project.org/package=nasapower

Sterling, C. A., Hermida, M. A., Rodríguez, C. H., Salas, Y. M., Nieto, M. N., and Caicedo, D. F. (2015). Reacción a Moniliophthora roreri en Theobroma spp. en Caquetá, Colombia. *Summa Phytopathol.* 41, 183–190. doi: 10.1590/0100-5405/2026

Suárez, J. C., Ngo Bieng, M. A., Melgarejo, L. M., Di Rienzo, J. A., and Casanoves, F. (2018). First typology of cacao (*Theobroma cacao* L.) systems in Colombian Amazonia, based on tree species richness, canopy structure and light availability. *PLoS One* 13:e0191003. doi: 10.1371/journal.pone.0191003

Trebissou, C. I., Tahi, M. G., Munoz, F., Sanchez, L., N'Guetta, S. P. A., Cilas, C., et al. (2021). Cocoa breeding must take into account the competitive value of cocoa trees. *Eur. J. Agron.* 128:126288. doi: 10.1016/j.eja.2021.126288

Vaast, P., and Somarriba, E. (2014). Trade-offs between crop intensification and ecosystem services: the role of agroforestry in cocoa cultivation. *Agrofor. Syst.* 88, 947–956. doi: 10.1007/s10457-014-9762-x

Vargas, A., Somarriba, E., and Carballo, M. (2005). Dinámica poblacional del chinche (Monalonion dissimulatum Dist.) y daño de mazorcas en plantaciones orgánicas de cacao del Alto Beni, Bolivia. *Agroforestería Am.* 43, 72–76.

Wartenberg, A. C., Blaser, W. J., Gattinger, A., Roshetko, J. M., Van, M., and Six, J. (2017). Does shade tree diversity increase soil fertility in cocoa plantations? *Agric. Ecosyst. Environ.* 248, 190–199. doi: 10.1016/j.agee.2017.07.033

Zequeira-Larios, C., Santiago-Alarcon, D., Macgregor-Fors, I., and Castillo-Acosta, O. (2021). Tree diversity and composition in Mexican traditional smallholder cocoa agroforestry systems. *Agrofor. Syst.* 95, 1589–1602. doi: 10.1007/s10457-021-00673-z

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Blockchain and agricultural sustainability in South America: a systematic review

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In its fundamental role for food security in South America, sustainable agriculture faces the challenge of addressing the current and future needs of the region while ensuring profitability, environmental health, and social and economic equity. Currently, as support for sustainable agriculture, a significant transformation is observed in the agricultural landscape due to the development of advanced information systems. Technologies such as Artificial Intelligence, Machine Learning, and Blockchain have emerged as crucial tools to document and support sustainable agricultural processes. Blockchain technology has proven to be highly beneficial for sustainable agriculture, effectively addressing a significant issue in the agricultural supply chain by providing solutions for transparent and traceable processes. This technology solves the problem by establishing a permanent and open record of all transactions and activities in the supply chain, allowing consumers and stakeholders to track the origin and quality of agricultural products, thereby fostering trust and fair trade. For this reason, this article conducted a review of the current state of blockchain technology in sustainable agriculture, aimed at researchers and farmers in South America. The advantages and disadvantages of blockchain technology were identified, focusing on technologies developed and tested during the design and pilot phases. The PRISMA methodology was used in this review, and documents were searched in Scopus and Web of Science databases. Six hundred and fifty-six articles were identified and selected (2018–2023 period), but only 104 met the eligibility and inclusion criteria. The findings indicate a 30% increase in the adoption of decentralized applications (DAPs) powered by blockchain in the agribusiness sector compared to the previous year. After a thorough analysis, it has been determined that smart contracts, non-fungible tokens for digital assets, and blockchain oracles will provide promising solutions for sustainable agricultural technology in the future.

KEYWORDS

blockchain, sustainable agriculture, traceability, smart contracts, agribusiness, review

1 Introduction

As a fundamental pillar of food security in South America, sustainable agriculture faces the challenge of meeting the current and future needs of the region while ensuring profitability, environmental health, and social and economic equity (Mba et al., 2020). In this context, sustainable agriculture emerges as an essential pillar, contributing to the four critical aspects of food security: availability, access, utilization, and stability; addressing the environmental, social, and economic dimensions of sustainability outlined by the United Nations Food and Agriculture Organization (FAO) (Resources, Forest, and Assessment Working, 1962).

Currently, a significant transformation is observed in the agricultural sector and its supply chain, encompassing all stages from planting to the end consumer. This process includes activities such as cultivation, harvesting, processing, storage, transportation, and sale, ensuring the efficient delivery of fresh food and agricultural products through the development of advanced information systems that support sustainable agriculture. Technologies like Artificial Intelligence (AI), Machine Learning (ML), and Blockchain have emerged as crucial tools to document and assist agricultural processes (Ordonez et al., 2023). In particular, Blockchain, introduced in 2009 alongside the creation of Bitcoin by Satoshi Nakamoto, is a decentralized network where data is stored and shared among nodes, eliminating central authority (Treiblmaier, 2019). Nodes mutually validate transactions, creating a distributed ledger. Considered a technological innovation, it stands out for its autonomy, anonymity, and data immutability. Interconnected Blockchain forms a distributed database, allowing the storage, linking, and retrieval of transaction information (Zhu and Kouhizadeh, 2019). This technology is used in situations requiring privacy, identity control, and permissions, providing immutability, transparency, and instant security by eliminating intermediaries and ensuring the integrity of information, demonstrating a significant impact on traceability and other aspects of the agricultural supply chain (Li et al., 2021; Song and Li, 2021).

In this context, the essential role of this technology is emphasized in fostering trust and collaboration among various actors in the agricultural supply chain, whether partners or competitors. Blockchain provides end-to-end visibility when working with farm products, recording every relevant event from production to delivery to the end consumer (Astill et al., 2019). This approach ensures traceability and safeguards protection, equity, and confidentiality at each stage of the process, determining and contributing to fulfilling the pillars of sustainable agriculture outlined by the FAO (Reyes et al., 2020).

Blockchain applications go beyond traceability, including transaction certification, smart agriculture, and order logistics management in agribusiness (Westerkamp et al., 2020; Sharma et al., 2022). Although various investigations have been carried out on the subject, this review aims to identify the advantages and disadvantages of the current use of Blockchain to support sustainable agriculture and agribusiness, with an emphasis on its application in South America. It analyzes the advantages and disadvantages of implementation in sustainable agriculture and highlights the usage and development of this technology in South America and its relationship with the sustainability pillars (availability, access, utilization, and stability) defined by the FAO (Reyes et al., 2020).

The PRISMA methodology (Moher et al., 2009) was applied, identifying 656 documents and selecting 17 supporting the relevance of Blockchain in agricultural sustainability. Two research questions were addressed, revealing that the technology is used in four South American countries in various contexts. This includes the development of decentralized applications for food traceability (DAPs), the authentication of originality using Non-Fungible Tokens (NFTs), and the validation of intermediaries through smart contracts. The findings indicate a significant growth in the adoption of this technology. This work is organized into sections detailing the methodology, analyzing the literature, examining the application of Blockchain in sustainable agriculture (with a regional focus on South America), presenting conclusions, and finally outlining future research areas.

2 Process methodologic

The purpose of this review aims to identify the advantages and disadvantages of the current use of Blockchain to support sustainable agriculture and agribusiness, with an emphasis on its application in South America (Singh et al., 2022).

Based on this objective, the following research questions (RQs) are posed, guiding the development of the review:

- **RQ1.** What are the advantages and disadvantages of the use and adoption of blockchain in sustainable agriculture?
- **RQ2.** Which South American countries are adopting blockchain technology in their agricultural processes?

To address and answer these research questions and achieve the objective, the methodological procedure based on the phases of identification, selection, eligibility, and inclusion of the PRISMA (systematic literature review) is utilized, as depicted in Figure 1 (Moher et al., 2009).

In the development of phase number 1 of the methodology, the literature search string is defined. This is applied in the most recognized digital libraries that contain the largest number of scientific documents related to this research. In this document, Web of Science and Scopus are used. Similarly, this phase involves establishing the research protocol, which includes defining search terms using keywords and various logical operators such as 'OR' and 'AND', as detailed in Table 1. After obtaining a result of 656 documents, these documents are loaded into tools like ScientoPy to process all the documents. To conclude this phase, it is determined that there are 316 duplicate documents. Therefore, for phase two, there are 340 documents that will be evaluated under the selection criteria.

In Phase 2 of the methodology, the literature selection criteria are applied. For this research, studies are considered relevant if they meet the following criteria: (a) the publication must be a paper presented at a conference or published in a peer-reviewed journal, (b) the articles must fall within the period from 2018 to 2023, (c) articles with small samples, deficient methodologies, or unreliable results, (d) articles that provide only an abstract and do not have access to the full text, and (e) articles only in the English language.

For the language criterion, the decision is made to include only articles in English because it is widely accepted as the predominant language in scientific and technological literature worldwide. Most renowned conferences and scientific journals use English as the primary means of communication, facilitating the global dissemination of research. Additionally, the preference for English helps ensure accessibility and understanding by the international scientific community. The use of a common language simplifies communication and knowledge exchange among researchers from different countries and regions (Hamel, 2007). For details on the number of articles discarded for each criterion, reference can be made to Table 2.

In the third phase, with the remaining 175 articles, exclusion criteria were applied, excluding studies that did not specifically address the use of blockchain technology in sustainable agriculture or agribusiness. All titles, abstracts, and keywords were thoroughly

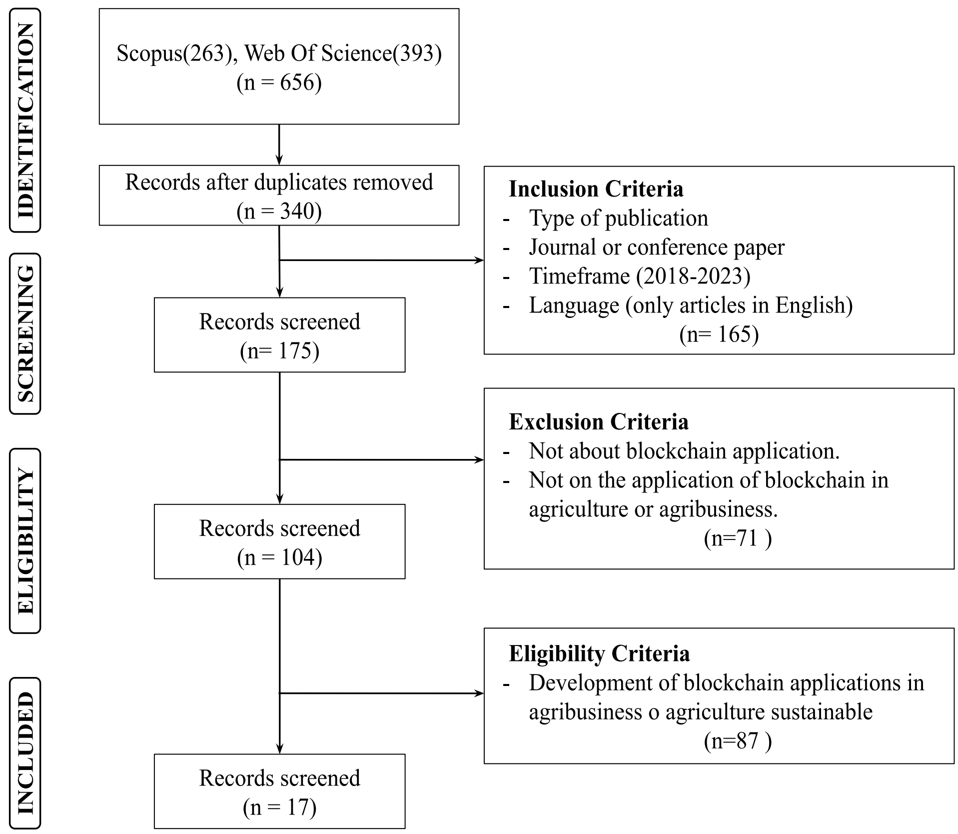

FIGURE 1
PRISMA flow diagram for systematic review.

TABLE 1 Search string.

Digital Bookstores	Search string design
SCOPUS	(TITLE-ABS-KEY (BLOCKCHAIN) AND TITLE-ABS-KEY (TRACEABILITY) OR TITLE-ABS-KEY (AGRICULTURE) OR TITLE-ABS-KEY (AGRIBUSINESS) AND TITLE-ABS-KEY (SUSTAINABILITY))
WOS	((((TI = (BLOCKCHAIN)) AND TI = (TRACEABILITY)) OR TI = (AGRICULTURE)) OR TI = (AGRIBUSINESS)) AND TI = (SUSTAINABILITY)

examined at this stage to determine which documents met the criteria. The following statements were used for this purpose:

- The article addresses the subject of blockchain-based applications in smart and sustainable agriculture.
- Articles were sought on the adoption of blockchain technology for smart and sustainable agriculture.
- Specific articles were needed on suggested blockchain architectures and models for sustainable agriculture.
- The article discusses the benefits and barriers of blockchain applicability for smart and sustainable agriculture.
- Among the keywords, "blockchain," "smart agriculture," "enablers," "barriers," "food supply chain," "e-agriculture systems," "traceability," "provenance," "trust," "safety," and "transparency" were identified.

After a comprehensive and meticulous review of the eligible articles, it was determined that a total of 71 articles did not meet the criteria mentioned earlier, resulting in 104 relevant investigations for this review.

In phase four, the inclusion stage of the reviewed articles is carried out, contributing to the development of the overall objective, and addressing the research questions. During this stage, the importance of employing a systematic literature review (SLR) approach to conduct reliable and reproducible literature reviews is highlighted. This involved conducting qualitative analyses and evaluations of relevant articles using thematic analysis to group and synthesize the main themes, thus improving the accuracy and completeness of the data (Carrera-Rivera et al., 2022). Thematic analysis, as described in the work (Braun et al., 2006), encompasses six stages: familiarization with the data, initial code creation, theme identification, review, definition, and naming.

During this stage, it was identified that 87 articles were narrative reviews or purely technical investigations, lacking relevant information on the implementation of blockchain technology in agribusiness and sustainable agriculture. Additionally, they did not focus on developments related to South American countries. Due to this

TABLE 2 Discarded articles due to selection criteria.

Criteria	Article O conference paper	Period 2018–2023	Methodology	Articles only abstract	Different English languages	Total articles
NUMBER of articles eliminated	48	69	15	13	20	165

limitation, the decision was made to disqualify these articles, ultimately including 17 articles for analysis.

Next, in Table 3, the selected articles are presented, classified into two main themes: blockchain and sustainable agriculture, and the role of blockchain in agribusiness. The 17 articles were categorized into these themes, and common patterns among the authors were examined for classification. Consequently, the relevant results and connections that contribute to addressing the research questions are presented.

2.1 Results

The relationship between terms and their grouping into various categories is crucial in researching and analyzing a topic. In this context, Figure 2 provides a chronological representation that identifies how words are related and evolve. Understanding and contextualizing vital elements in sustainable agriculture, implementing Blockchain within this context, and effectively focusing and guiding the review are essential. This approach significantly contributes to defining the scope and relevance of the review. Highlighting these terms drives to focus on the most critical and current aspects of the topic, which is essential to ensure that the review is aligned with the latest advancements in sustainable agriculture and the application of blockchain technology.

The ability to track these trends over time yields valuable insights into the trajectory and dynamics of research within this field. The pertinent issues identified through this analysis hold paramount significance today, addressing pivotal concerns within agriculture and the integration of blockchain technology. In yellow, the highlighted topics establish direct connections with the innovation and design of systems incorporating Blockchain and its facilitation of the supply chain and agribusiness. Furthermore, these areas align seamlessly with contemporary applications of blockchain technology, emphasizing innovation and system design alongside its pivotal role in supporting the supply chain and agribusiness.

In the sphere of sustainable agriculture, substantial strides are being taken through the integration of blockchain technology. In this context, pivotal concepts such as economic growth, agroecology, yield, quality, intensification, wheat, biochar, financial sustainability, social sustainability, and performance have surfaced as this state-of-the-art technology's primary focal points and integral applications.

This term analysis aims to examine the correlation between these terms and the countries incorporating technology into their sustainable agricultural practices since the identification of the technology started with the first publications on the subject, where relevance is observed to have emerged since the year 2009. Globally, it can be observed that the United States leads developments in blockchain technology in sustainable agriculture, followed by India, Italy, the United Kingdom, China, Spain, France, Brazil, Canada, and Australia. This ranking is derived from the total number of articles on the implementation of blockchain in agricultural processes, categorized by those published before and after 2021, as identified in different geometric figures, as shown in Figure 3. Notably, Brazil (gray circle) has emerged as a leading country in South America, showing significant adoption of blockchain technology in its sustainable agricultural processes. For a deeper examination of the contributions of this country, the research includes a dedicated section where the contributions of this technology in individual countries are determined and analyzed.

Based on this analysis, the description of the selected articles, categorized into two groups, contributing to answering the research questions, proceeds as outlined below.

2.2 Blockchain sustainability

Blockchain technology, as a distributed ledger system, has emerged as a critical enabler for enhancing sustainable agriculture, agricultural resource management, innovation in agriculture, urban agriculture, and agribusiness. The following paragraphs describe the most relevant results obtained through this technology.

Saberi et al. (2019) investigate the adoption barriers of Blockchain technology in the supply chain, affecting partners, employees, and stakeholders. They highlight technological barriers stemming from the technology's immaturity, emphasizing the need for further research in scalability. They also propose areas of study to address post-adoption issues and recommend implementing standards and regulations to ensure Blockchain's interoperability and security in the supply chain.

The article Dos Santos et al. (2021) proposes using smart contracts and non-fungible tokens (NFTs) as an efficient and fraud-resistant tool to demonstrate the sustainability of specific crops. This technology enables farmers to be certified by any authority, extending their certificates as NFTs throughout the supply chain to the consumer. Furthermore, it emphasizes the presence of economic incentives for participants, encouraging adoption and promoting sustainability while combating "greenwashing."

Implementing blockchain technology in supply chain management aims to promote sustainability in various regions, including countries like China and South Africa. Notably, blockchain adoption in supply chain management is occurring globally, encompassing developed and developing countries. In this context, eight key themes motivating the adoption of this technology in the agri-food supply chain have been identified Kshetri (2021). These themes range from the need to ensure traceability and transparency of food to facilitating financing and market access, thus promoting sustainability and social responsibility Yogarajan et al. (2023). However, critical research gaps are highlighted, such as the lack of studies in diverse cultural environments, limited research on logistical

TABLE 3 Summary of the identified studies and their correlation with the RQs.

Item	Cited by	Title	Author	Group	RQs
1	1,539	Blockchain technology and its relationships to sustainable supply chain management	Saberi et al. (2019)	Blockchain sustainability	RQ1
2	26	Third party certification of agri-food supply chain using smart contracts and blockchain tokens	Dos Santos et al. (2021)	Blockchain sustainability	RQ1
3	98	Exploring the hype of blockchain adoption in agri-food supply chain: a systematic literature review	Yogarajan et al. (2023)	Blockchain in agribusiness	RQ1, RQ2
4	91	Blockchain and sustainable supply chain management in developing countries	Kshetri (2021)	Blockchain sustainability	RQ1, RQ2
5	75	Blockchain as a sustainability-oriented innovation?: Opportunities for and resistance to Blockchain technology as a driver of sustainability in global food supply chains	Friedman and Ormiston (2022)	Blockchain sustainability	RQ1, RQ2
6	53	Toward an agriculture solution for product supply chain using Blockchain: case study Agro-chain with BigchainDB	Orjuela et al. (2021)	Blockchain in agribusiness	RQ1
7	33	Analysis of Blockchain's enablers for improving sustainable supply chain transparency in Africa cocoa industry	Bai et al. (2022)	Blockchain in agribusiness	RQ2
8	10	A critical analysis of the integration of Blockchain and artificial intelligence for supply chain	Charles et al. (2023)	Blockchain sustainability	RQ1
9	14	An evidence of distributed trust in blockchain-based sustainable food supply chain	Joo and Han (2021)	Blockchain sustainability	RQ1
10	11	The potential of blockchain technology in the transition toward sustainable food systems	Wünsche and Fernqvist (2022)	Blockchain sustainability	RQ1
11	9	Blockchain technology in wine chain for collecting and addressing sustainable performance: an exploratory study	Luzzani et al. (2021)	Blockchain in agribusiness	RQ2
12	4	Design of a blockchain-based decentralized architecture for sustainable agriculture: research-in-progress	Akella et al. (2021)	Blockchain in agribusiness	RQ1
13	6	Smart contract for coffee transport and storage with data validation	Valencia-Payan et al. (2022)	Blockchain sustainability	RQ2
14	52	Using system dynamics to analyze the societal impacts of blockchain technology in milk supply chainsrefer	Mangla et al. (2021)	Blockchain in agribusiness	RQ1
15	4	Smart contract and Web DApp for traceability in the olive oil production chain	Fernandes et al. (2022)	Blockchain sustainability	RQ1
16	14	Blockchain is not a silver bullet for agro-food supply chain sustainability: Insights from a coffee case study	Bager et al. (2022)	Blockchain in agribusiness	RQ1, RQ2
17	3	Blockchain trust impact in agribusiness supply chain: a survey, challenges, and directions	Nasir et al. (2022)	Blockchain in agribusiness	RQ1

and operational effects, absence of studies on quality management in blockchain adoption, lack of consideration for socio-environmental costs, and limited research on the impact in developing countries.

In Friedman and Ormiston (2022), a methodology is proposed based on interviews with experts in food supply chains, providing a comprehensive view of the use of Blockchain as both a practical tool and a philosophy to address sustainable challenges. The study identifies various forms of resistance, including functional and psychological barriers and obstacles to implementing the technology. It contributes significantly to the literature on sustainability-focused innovation and innovation resistance theory by shedding light on blockchain technology's role and perceived limitations in food supply chains.

On the other hand Bai et al. (2022), based on the theoretical framework of Technology-Organization-Environment (TOE), present a hierarchical enabling framework to enhance the transparency of Sustainable Supply Chain (SSCT) through blockchain technology in the cocoa industry. Using the Best-Worst Method (BWM), the weights of the main facilitators and sub-facilitators are evaluated in a real case of the cocoa supply chain in an emerging African economy.

The results highlight that "Technical Characteristics" are the leading facilitator, and the most significant sub-facilitators include "blockchain smart contract," "blockchain security," and "product component tracking. This approach provides decision-makers and supply chain managers with a framework and method to develop effective strategies for blockchain implementation, thereby improving SSCT.

In Valencia-Payan et al. (2022), a smart contract is designed to carry out traceability and monitoring of the stages of transportation and storage, as well as the condition of coffee beans. The smart

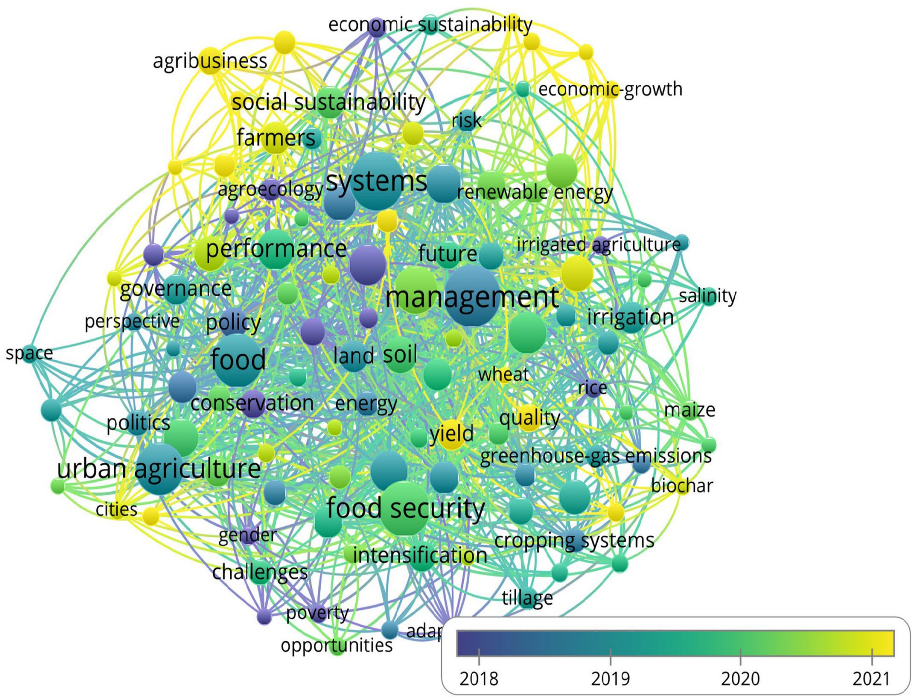

FIGURE 2
Topics related to the adoption of Blockchain in sustainable agriculture.

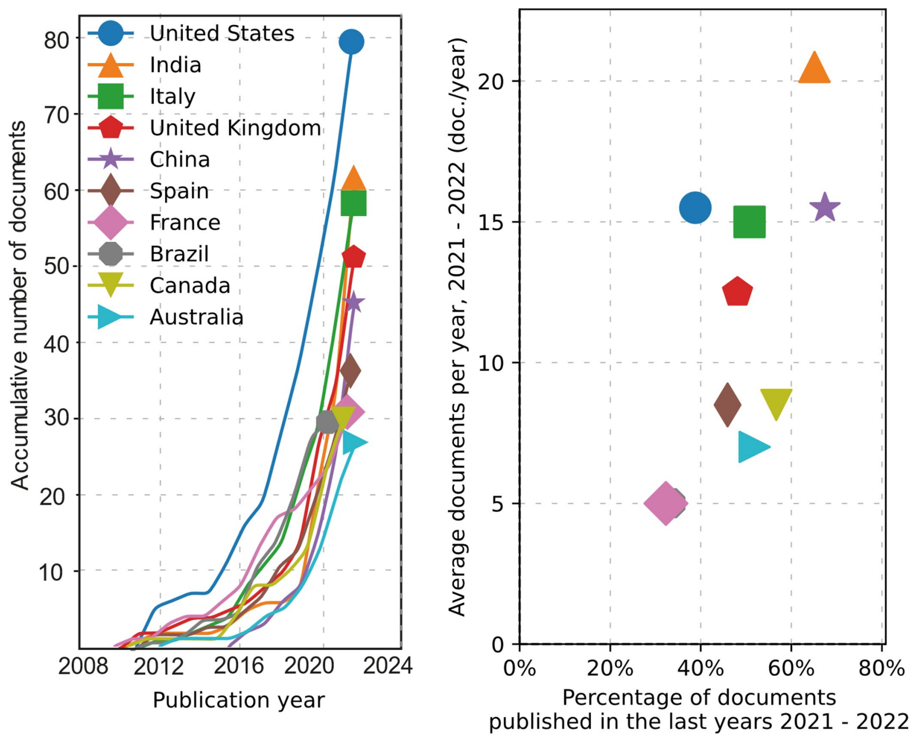

FIGURE 3
Work related to Blockchain and agriculture worldwide, before and after 2021.

contract collects data from sensors placed in coffee bags. It validates the information to ensure that the coffee beans are transported and stored under appropriate conditions, verifying humidity and temperature. It contributes to the farmer making informed decisions regarding pre-sale management and achieving better profits by considering coffee certification schemes.

The study Joo and Han (2021), explores the preference for private or permissioned blockchains, such as Hyperledger Fabric, compared to public blockchains for supply chain management. Food safety emerges as a primary concern, and the adoption of permissioned blockchains since 2018 has enhanced transparency, traceability, and security in the supply chain. Additionally, an analysis of the determinants of distributed trust in the blockchain-based supply chain is conducted, emphasizing the critical importance of transparency, traceability, and security to foster trust and user satisfaction in a sustainable supply chain. In this context Akella et al. (2021), an architecture designed for real-time operations using Blockchain, an area that has been scarcely studied so far, is proposed. Implementing this architecture has identified gaps, and work is currently underway to integrate smart contracts to achieve efficient and sustainable agriculture. The anticipated results will benefit agricultural value chains, intermediaries, farmers, and food suppliers in Australia.

Based on Fernandes et al. (2022), the authors design a software solution by implementing blockchain technology and smart contracts to ensure the traceability of olive oil. It was identified that, when making their purchases, consumers focus not only on food brands but also on characteristics such as nutritional value and sustainability. These aspects are directly linked to all stages of the value chain. The smart contract design ensures that this information is accessible and reliable for consumers, strengthening their trust. The proposal focuses explicitly on traceability in the production chain, addressing indicators of quality, social sustainability, and environmental sustainability.

2.3 Blockchain in agribusiness

Likewise Charles et al. (2023), explored the integration of artificial intelligence (AI) with blockchain technology as a promising strategy to address challenges in supply chain management. Combining both is a strategic solution, generating benefits such as more solid results. The fundamental reason for this research lies in the ability of these technologies to overcome limitations and improve various aspects of supply chains. By analyzing large volumes of data, AI powers decision-making and predictive analysis in chain management, offering an advanced and automated approach to extracting valuable information from historical data, such as predicting future demands and forecasting sales, thus contributing to agribusiness.

This research Wünsche and Fernqvist (2022) establishes a study to compare supply chains with Blockchain, proposing investigations into blockchain service design, user experiences, and practical issues in the documentation and certification of current systems. It suggests the inclusion of qualitative assessments of companies throughout the chain, including farmers and small agri-food businesses. It advocates for quantitative studies with the food industry to deepen understanding and improve standards for data exchange and transparency, considering the role of policies. Additionally, it proposes comparing the environmental sustainability of conventional food systems and those facilitated by blockchain, using tools such as life cycle assessment for quantitative reasoning on the value blockchain can contribute to more sustainable food systems.

In Luzzani et al. (2021), exploratory research was designed to investigate the potential benefits and challenges of implementing blockchain technology in the wine industry. Divided into three phases, it addressed specific questions. A systematic literature review was conducted in the first phase on using Blockchain in supply chain and sustainability. The second phase involved surveys of wineries, assessing their knowledge and willingness to adopt Blockchain. The third phase included qualitative interviews with a winery that had already implemented the technology. The study identified benefits such as improved transparency and traceability, data collection on the sustainable performance of wine producers, and enhanced communication among supply chain actors. It also highlighted success stories like the AgriDigital platform in Australia and TE-FOOD in Europe. The need for increased blockchain adoption and data privacy and security considerations for agribusiness development were emphasized. Based on Mangla et al. (2021), the crucial importance of transparency, traceability, and security provided by blockchain technology is established as effective measures against corruption and fraud in the system. An exploration is conducted into the social impacts resulting from the introduction of blockchain technology in the milk supply chain, considering aspects such as rural development, food fraud, animal health, and food safety. The proposal to map and analyze milk supply chains aims to improve social sustainability, seeking to understand how the adoption of blockchain technology influences society and identify opportunities for agribusiness and specific application areas in these supply chains. Orjuela et al. (2021), propose designing and developing a blockchain technology-based platform to enhance traceability and transparency in the agricultural supply chain. The platform utilizes a blockchain database in BigchainDB to store information about farm products, including their origin, quality, and location. It also employs a business model based on smart contracts to automate negotiation and payment processes within the supply chain. Furthermore, it suggests using technologies such as RFID and GPS to improve the accuracy of product location information.

In Bager et al. (2022), the potential of blockchain technology to enhance sustainability in coffee supply chains was assessed, focusing on traceability and transparency. While the pilot implementation highlighted benefits, it also indicated that blockchain technology is not a universal solution to the sustainability challenges of the coffee industry. Despite its reputation as the ultimate system for transparency and sustainability, the study suggests that the true strength of blockchain technology in agri-food chains might lie in the digitization of the supply chain to increase efficiency and reduce costs, disputes, and fraud. The analysis revealed that blockchain implementation can be costly and offer few benefits in cases like non-segregated chains with numerous small-scale farmers. Although specialized chains might be ideal candidates, the additional value of Blockchain could be limited. Furthermore, the importance of digitization to enhance efficiency and transparency was emphasized, indicating that centralized digital solutions could be equally effective. The study underscores the need to understand and minimize real-world barriers before fully leveraging the benefits of digitization and decentralization.

Finally, Nasir et al. (2022), a state-of-the-art review is conducted with the primary objective of presenting the evolution of Blockchain technology, focusing on enhancing trust in the management of agribusiness supply chains and addressing trust inefficiency issues. The research centers on the agribusiness supply chain networks, analyzing issues related to building trust networks based on Blockchain among participants in the data exchange throughout the information flow of the supply chain. Additionally, the paper addresses the research challenges during the design and explores potential solution directions for agribusiness.

3 Discussion RQ1, RQ2

In the upcoming sections, we will delve into the findings that stem from the research questions, which played a pivotal role in shaping this systematic review.

> RQ1: ¿What are the advantages and disadvantages of blockchain use and appropriation in sustainable agriculture?

Figure 4 graphically represents the advantages and disadvantages of blockchain technology in sustainable agriculture. Based on this review, we are prepared to address the research question.

Implementing blockchain technology in sustainable agriculture has brought various benefits and disadvantages. Regarding the advantages, transparency stands out by allowing the secure recording of data to trace the origin of agricultural products, which is essential to ensure their sustainability and traceability in the food supply chain (Wünsche and Fernqvist, 2022). The outstanding efficiency in data management through blockchain technology becomes a key focal point in sustainable agriculture. This innovation enables a secure and immutable data record and is prioritized as a fundamental element to drive transparency and traceability throughout the agricultural supply chain. The tool's capability to securely trace the origin of products ensures authenticity and directly translates into the related sustainability of such products. In this context, data management efficiency through blockchain becomes the essential tool to identify sustainable agricultural practices and expose any harmful activities to the environment, ensuring sustainability certificates and organic product labels, combating fraud in the industry, and empowering consumers (Song, 2020).

The use of blockchain for traceability is evident in systems designed and implemented in agricultural products such as coffee, oil, wine, and meat. This approach has significantly contributed to the sustainable development of farming processes. Applying blockchain in these sectors promotes sustainable agricultural practices and gives consumers greater confidence in the origin and quality of products (Valencia-Payan et al., 2022).

On the other hand, there are significant drawbacks; farmers face substantial barriers when adopting blockchain technology, primarily due to associated costs. Specialized technological infrastructure, customized development, and personnel training in blockchain incur significant initial expenses. Integrating with existing systems and the need for technical personnel to manage and maintain the technology adds layers of investment. Maintenance and update costs escalate the financial burden over time. In agricultural settings, particularly in rural areas or developing countries, these costs can pose a significant barrier to the widespread adoption of blockchain technology (Kshetri, 2021).

The scalability of the blockchain is another challenge, as processing speed can decrease as more data is added. It can be problematic in environments with high transaction volumes, such as large-scale agriculture (Sundarakani et al., 2021).

The dependence of blockchain connectivity in the developing agroindustry emerges as a critical factor in its implementation. The effectiveness of this technology is intrinsically linked to the availability and quality of internet connectivity. The ability to transmit data efficiently and in real-time, crucial for traceability and transparency in the agricultural supply chain, requires a robust connectivity infrastructure. In rural environments or developing regions where connectivity infrastructure may be limited, dependence on a blockchain can pose substantial challenges (Yogarajan et al., 2023).

Similarly, the lack of alignment between existing regulations and the decentralized nature of blockchain creates uncertainty and complexities for participants in the agricultural industry. Ambiguities in aspects such as ownership and data management can slow down adoption. Furthermore, the rapid evolution of technology may outpace existing regulatory frameworks, leading to gaps in oversight. Despite these concerns, well-designed regulation could provide a robust legal framework, addressing privacy and security, thus promoting trust and widespread adoption (Singh and Vishwakarma, 2022).

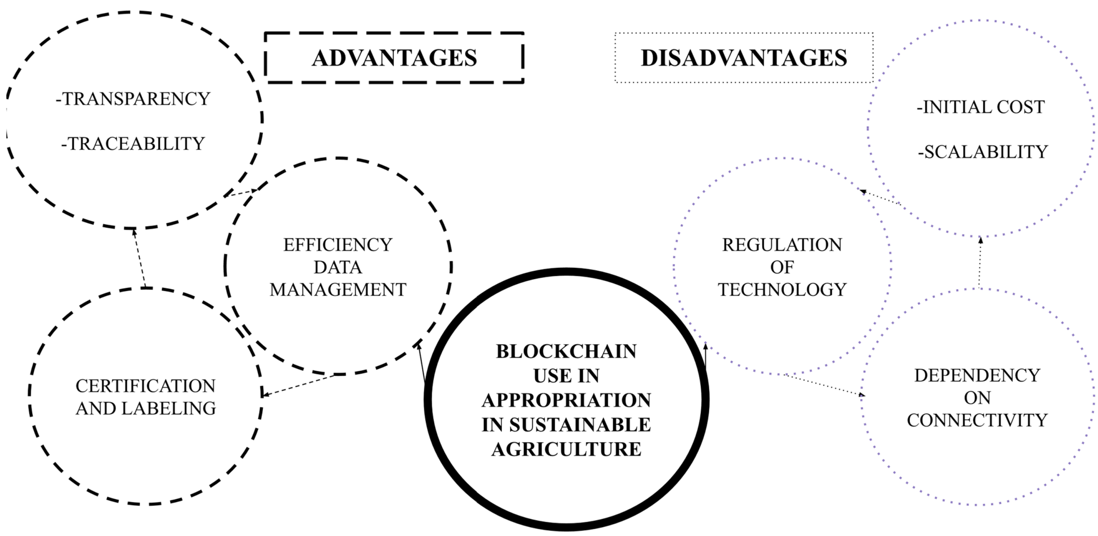

FIGURE 4
Advantages and disadvantages of blockchain technology in sustainable agriculture.

Furthermore, using smart contracts and cybersecurity in agriculture raises some criticism and concerns. Some of them are:

- Technical complexity: Implementing smart contracts and integrating Blockchain into the agricultural supply chain requires advanced technical knowledge, challenging farmers and other stakeholders unfamiliar with these technologies (Quayson et al., 2021).
- Data privacy: The use of Blockchain meant that data was permanently stored and accessible to all participants in the network, raising concerns about the confidentiality of sensitive data such as financial information or farmers' data (Kshetri, 2021).
- Scalability: The ability of blockchain technology to handle large volumes of transactions may be limited, which represents an obstacle to its large-scale implementation in the agricultural supply chain, where numerous transactions are generated daily (Sundarakani et al., 2021).
- Costs: The adoption of smart contracts and Blockchain involves significant costs, such as investment in technological infrastructure and network maintenance, as a barrier to the participation of small farmers or companies with limited resources (Joo and Han, 2021).
- Interoperability: The lack of common standards and protocols in blockchain technology creates difficulties in interoperability between different systems and platforms, limiting the ability of agricultural supply chain actors to collaborate and share data efficiently (Singh and Vishwakarma, 2022).

> RQ2: ¿Which South American countries are adopting blockchain technology in their agricultural processes?

The adoption of blockchain technology in the agribusiness sector in South America is experiencing steady growth, driven by determining factors. Essentially, Blockchain has proven to be a highly effective solution for addressing challenges related to transparency and traceability in the agro-industrial supply chain (Sadiq and Anal, 2023). In response to the increasing demand from consumers who seek precise knowledge about the origin and history of the products they consume, blockchain technology enables detailed tracking from the moment of production until it reaches the consumer's table. This phenomenon is evident in countries such as Colombia and Chile see Figure 5 (Abad-Segura et al., 2021; Orjuela et al., 2021; Bager et al., 2022), where traceability systems and strategies have been recently implemented in agricultural processes. According to the FAO, this initiative is directly linked to the access pillar, which determines the best practices used in agriculture, livestock, forestry, and fishing.

Brazil stands out as one of the prominent leaders in adopting blockchain technology, developing various applications for specific purposes. Its pivotal role in enhancing the supply chain and transparency in South American agribusiness is noteworthy, with food security being a key pillar for the country. The applications designed and linked to Brazil focus on determining the quality and safety of agricultural products (Dos Santos et al., 2021).

On the other hand, Peru is the most recent country to join the adoption of this technology, directing its efforts toward optimizing processes related to the FAO pillar of availability. In this context, they have developed blockchain-based components to identify the production, imports, storage, and tracking of crops, all to ensure the integrity of data and information associated with each (Abad-Segura et al., 2021).

South American countries have delved deeper into blockchain technology within the agribusiness sector, revealing varying degrees of reach and adoption across the region. The following section provides an overview of the advances and studies using blockchain technology in agricultural processes.

- In Brazil, a mobile application was developed to certify the agri-food supply chain through smart contracts and blockchain tokens. It allowed farmers to request inspections for their wine harvests, issuing blockchain tokens that authenticated the quality and authenticity of the harvest. Consumers could verify the authenticity of the certificate by scanning the product. The application used ERC-1155 NFT and ERC-20 tokens to represent harvests and certificates, being implemented on Ethereum through smart contracts in Solidity. Public access to the source code of the smart contracts on the Ethereum network was provided for consumer audit and review (Dos Santos et al., 2021).
- The authors advocate for adopting blockchain technology in coffee supply chains in Colombia to enhance sustainability (Bager et al., 2022). Emphasizes the strength of blockchain in digitizing the supply chain, improving efficiency, and reducing costs, disputes, and fraud in agri-food chains. The importance of understanding and minimizing real-world barriers before fully leveraging the benefits of digitization and decentralization is underscored. In contrast, (Valencia-Payan et al., 2022) propose a smart contract to trace coffee beans' transportation and storage stages, monitoring their condition based on humidity and temperature. The proposal pursues greater traceability and quality control in the supply chain.
- In Chile, a study was conducted to identify emerging trends in blockchain technology research for secure accounting management. Reliable quality indicators were obtained by applying mathematical and statistical techniques to a sample of 1,130 articles from Elsevier's Scopus database. The study demonstrated the usefulness of blockchain technology in areas such as supply chain and logistics, providing solutions for traceability and transparency. It also highlighted new research areas like Blockchain and data privacy, cybersecurity, digital identity, and renewable energy systems. The findings are relevant for academics, researchers, and blockchain developers (Abad-Segura et al., 2021).
- In Peru, a review of the state of the art focused on agriculture and smart contracts to explore how blockchain technology and smart contracts enhanced transparency, traceability, and quality control in the agri-food supply chain. It was emphasized that the combination of Blockchain, the Internet of Things (IoT), and smart contracts enabled a transformed digital agricultural ecosystem where traceability and verification of food quality were achieved reliably and transparently. Additionally, it was highlighted that blockchain-based smart contracts helped address food safety issues by documenting all transactions in a distributed manner and maintaining an immutable record of the same (Charles et al., 2023)

FIGURE 5
Countries that use Blockchain and their relationship with the pillars of sustainability.

After conducting this analysis on the adoption of technologies in sustainable agricultural processes in South America, the economic diversity of the region becomes evident, with countries at different stages of development. This diversity directly impacts the availability of resources and investment in technologies such as blockchain. The technological infrastructure varies between regions, influencing the adoption of blockchain in agriculture based on connectivity and access to emerging technologies. While Brazil stands out as a powerhouse in South America and a pioneer in regional technological development, each country has specific characteristics, such as predominant crop types and agricultural practices, that influence the adoption of technologies like blockchain (Da Silveira et al., 2023). To incorporate this technology in other South American countries, there is a perceived need for government regulations, educational awareness, local initiatives, collaborations, and governmental support as key factors for adoption.

In contrast, in countries like the United States, China, and European countries, the implementation of blockchain technologies occurs gradually, addressing different services. These countries make significant investments to enhance supply chain management and traceability of agricultural products, utilizing blockchain to address authenticity, transparency, and product security (Samadhiya et al., 2023).

4 Conclusions and future work

After conducting this comprehensive review, it is concluded that blockchain technology emerges as an essential tool in sustainable agriculture and the traceability of agricultural products. The immutability and transparency of Blockchain ensure the integrity of records throughout the supply chain, not only promoting food safety by enabling swift responses to potential issues but also empowering consumers by providing verifiable information about the origin and quality of the products they purchase. This transparency is crucial for driving the demand for environmentally friendly and ethical products while rewarding farmers who embrace sustainable practices. Blockchain technology is a fundamental pillar for effectively and transparently addressing these challenges in an increasingly sustainability-conscious world concerned with food traceability.

The introduction of blockchain technology in sustainable agriculture has marked a significant advancement, albeit not without challenges. The transparency achieved through secure data recording has been crucial for confidently tracing the origin of agricultural products, enhancing their authenticity in the context of sustainability, and establishing effective traceability in the food supply chain. Identifying sustainable practices and exposing harmful environmental activities has proven to be a valuable tool.

However, drawbacks such as initial costs have acted as barriers to widespread adoption, especially in rural areas or developing nations. The need for training, the scalability challenge, and the reliance on a robust internet connection are critical aspects that require attention. The technical complexity, concerns about data privacy, scalability issues, costs, and interoperability in using smart contracts and cybersecurity in agriculture underscore the importance of addressing these aspects to maximize the benefits of blockchain technology in the agricultural domain. Despite the challenges, successful implementation has the potential to transform agriculture into a more sustainable and efficient model, providing a foundation for future development in this sector.

The adoption of blockchain technology in the agribusiness sector of South America is experiencing steady growth, serving as an effective solution to address transparency and traceability challenges in the supply chain. Brazil leads this revolution, supported by abundant research highlighting its applications and advantages in agribusiness.

Case studies in South America reveal blockchain technology's significant impact and versatility in agricultural supply chains. The Brazilian case highlights the successful implementation of Blockchain, smart contracts, and NFTs to certify wine harvests, enhancing authenticity and transparency for consumers. However, the Colombian study emphasizes the variability in the effectiveness of Blockchain, especially in non-segregated chains with small coffee farmers, underscoring the need for adaptive approaches. The Chilean research demonstrates the evolution of Blockchain into crucial areas such as data privacy and cybersecurity, expanding its utility in logistics and supply chain management. The Peruvian review underscores the transformative potential of Blockchain and smart contracts, ensuring traceability and food safety in a digitized agricultural ecosystem. The analysis of these valuable perspectives on the present and future of Blockchain emphasizes its essential role in the transparency and sustainability of agri-food chains, with the need to adapt according to the specific characteristics of each chain.

As a future endeavor to contribute to this field, efforts should be focused on addressing the identified challenges in this review. An example of this is to include strategies for reducing technology implementation costs in agriculture, especially for small farmers. Additionally, it is crucial to develop tailored training programs for farmers, providing them with the necessary skills and knowledge about the technology. Comprehensive cost–benefit analyses of its implementation and the design and establishment of interoperability standards are required, considering long-term impact assessments. Collaboration on policy recommendations is essential to guide the development of supportive regulatory frameworks that encourage responsible adoption of Blockchain in agriculture. These efforts aim to make blockchain technology more accessible, cost-effective, and impactful in transforming agriculture toward sustainability, requiring collaborative endeavors from researchers, policymakers, and stakeholders to overcome existing barriers and foster widespread adoption.

Furthermore, as future work, the need to review a greater number of articles is highlighted in order to carry out a comparison between South America and the development and implementation of blockchain in pioneering countries such as the United States, China, and European countries. For this, Spanish and Portuguese languages must be considered to obtain a broader scope of literature. This comparison is timely as these countries implement technology in their agriculture sustainably, following different standards. This analysis would not only identify best practices but also foster a more effective adoption of the technology, contributing to defining levels of technological integration in sustainable agriculture. This approach is essential for establishing robust practices and regulatory and educational frameworks, facilitating the successful adoption of the technology in diverse geographical locations.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

CO: Conceptualization, Methodology, Validation, Writing – original draft, Writing – review & editing. GG: Conceptualization, Investigation, Methodology, Resources, Validation, Visualization, Writing – review & editing. JC: Funding acquisition, Investigation, Methodology, Project administration, Resources, Validation, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Abad-Segura, E., Infante-Moro, A., González-Zamar, M.-D., and López-Meneses, E. (2021). Blockchain technology for secure accounting management: research trends analysis. *Mathematics* 9:631. doi: 10.3390/math9141631

Akella, G. K., Wibowo, S., Grandhi, S., and Mubarak, S. (2021). Design of a Blockchain-Based Decentralized Architecture for sustainable agriculture: research-in-Progress. In: *2021 IEEE/ACIS 19th International Conference on Software Engineering Research, Management and Applications, SERA 2021*. Institute of Electrical and Electronics Engineers Inc., pp. 102–107.

Astill, J., Dara, R. A., Campbell, M., Farber, J. M., Fraser, E. D. G., Sharif, S., et al. (2019). Transparency in food supply chains: a review of enabling technology solutions. *Trends Food Sci. Technol.* 91, 240–247. doi: 10.1016/j.tifs.2019.07.024

Bager, S. L., Singh, C., and Persson, U. M. (2022). Blockchain is not a silver bullet for agro-food supply chain sustainability: insights from a coffee case study. *Curr. Res. Environ. Sustain.* 4:100163. doi: 10.1016/j.crsust.2022.100163

Bai, C., Quayson, M., and Sarkis, J. (2022). Analysis of Blockchain's enablers for improving sustainable supply chain transparency in Africa cocoa industry. *J. Clean. Prod.* 358:131896. doi: 10.1016/j.jclepro.2022.131896

Braun, Virginia, and Clarke, V. (2006). Using Thematic Analysis in Psychology; In Qualittaive Research in Psychology. *Uwe Bristol.* 3, 77–101.

Carrera-Rivera, Angela, Ochoa, W., Larrinaga, F., and Lasa, G. (2022). How-to Conduct a Systematic Literature Review: A Quick Guide for Computer Science Research. *Methods X*. doi: 10.1016/j.mex.2022.101895

Charles, V., Emrouznejad, A., and Gherman, T. (2023). A critical analysis of the integration of Blockchain and artificial intelligence for supply chain. *Ann. Oper. Res.* 327, 7–47. doi: 10.1007/s10479-023-05169-w

Da Silveira, F., Da Silva, S. L. C., Machado, F. M., Barbedo, J. G. A., and Amaral, F. G. (2023). Farmers' perception of barriers that difficult the implementation of agriculture 4.0. *Agric. Syst.* 208:103656. doi: 10.1016/j.agsy.2023.103656

Dos Santos, R. B., Torrisi, N. M., and Pantoni, R. P. (2021). Third party certification of Agri-food supply chain using smart contracts and Blockchain tokens. *Sensors* 21:307. doi: 10.3390/s21165307

Fernandes, M. A., Cruz, E. F., and Rosado da Cruz, A. M. (2022). "Smart contract and web DApp for traceability in the olive oil production chain" in *Iberian Conference on Information Systems and Technologies, CISTI*. eds. A. Rocha, B. Bordel, F. G. Penalvo and R. Goncalves (Washington, DC: IEEE Computer Society)

Friedman, N., and Ormiston, J. (2022). Blockchain as a sustainability-oriented innovation?: opportunities for and resistance to Blockchain technology as a driver of sustainability in global food supply chains. *Technol. Forecast. Soc. Chang.* 175:121403. doi: 10.1016/j.techfore.2021.121403

Hamel, R. E. (2007). The dominance of English in the international scientific periodical literature and the future of language use in science. *Aila Rev.* 20, 53–71. doi: 10.1075/aila.20.06ham

Joo, J., and Han, Y. (2021). An evidence of distributed Trust in Blockchain-Based Sustainable Food Supply Chain. *Sustain. For.* 13:980. doi: 10.3390/su131910980

Kshetri, N. (2021). Blockchain and sustainable supply chain management in developing countries. *Int. J. Inf. Manag.* 60:102376. doi: 10.1016/j.ijinfomgt.2021.102376

Li, G., Chen, D., Zhang, J., Hu, F., and Zheng, G. (2021). Construction of simplified traceability system of agricultural products based on android. In: *IOP Conference Series: Earth and Environmental Science*. IOP Publishing Ltd.

Luzzani, G., Grandis, E., Frey, M., and Capri, E. (2021). Blockchain Technology in Wine Chain for collecting and addressing sustainable performance: an exploratory study. *Sustain(Switzerland)* 13:898. doi: 10.3390/su132212898

Mangla, S. K., Kazancoglu, Y., Ekinci, E., Liu, M., Özbiltekin, M., and Sezer, M. D. (2021). Using system dynamics to analyze the societal impacts of Blockchain Technology in Milk Supply Chainsrefer. *Transp. Res. Part E Logist. Transp. Rev.* 149:102289. doi: 10.1016/j.tre.2021.102289

Mba, C., Abang, M., Diulgheroff, S., Hrushka, A., Hugo, W., Ingelbrecht, I., et al. (2020). FAO supports countries in the implementation of the second global plan of action for plant genetic resources for food and agriculture. *Acta Hortic.* 1267, 197–208. doi: 10.17660/ActaHortic.2020.1267.30

Moher, D., Liberati, A., Tetzlaff, J., and Altman, D. G.The PRISMA Group (2009). Preferred reporting items for systematic reviews and Meta-analyses: the PRISMA statement. *PLoS Med.* 6, e1000097–e1000096. doi: 10.1371/journal.pmed.1000097

Nasir, N. M., Hassan, S., Zaini, K. M., and Nordin, N. (2022). Blockchain trust impact in agribusiness supply chain: a survey, challenges, and directions. In: *2022 IEEE Region 10 Symposium, TENSYMP 2022*. Institute of Electrical and Electronics Engineers Inc.

Ordonez, J., Alexopoulos, A., Koutras, K., Kalogeras, A., Stefanidis, K., and Martos, V. (2023). Blockchain in agriculture: a PESTELS analysis. *IEEE Access* 11, 73647–73679. doi: 10.1109/ACCESS.2023.3295889

Orjuela, K. G., Gaona-García, P. A., and Marin, C. E. M. (2021). Towards an agriculture solution for product supply chain using Blockchain: case study agro-chain with BigchainDB. *Acta Agric. Scand. B Soil Plant Sci.* 71, 1–16. doi: 10.1080/09064710.2020.1840618

Quayson, M., Bai, C., and Sarkis, J. (2021). Technology for Social Good Foundations: a perspective from the smallholder farmer in sustainable supply chains. *IEEE Trans. Eng. Manag.* 68, 894–898. doi: 10.1109/TEM.2020.2996003

Resources, Forest, and Assessment Working (1962). Terms and definitions. *J. Text. Inst. Proc.* 53, P290–P295. doi: 10.1080/19447016208688714

Reyes, S. R., Miyazaki, A., Yiu, E., and Saito, O. (2020). Enhancing sustainability in traditional agriculture: indicators for monitoring the conservation of globally important agricultural heritage systems (GIAHS) in Japan. *Sustainability* 12:656. doi: 10.3390/su12145656

Saberi, S., Kouhizadeh, M., Sarkis, J., and Shen, L. (2019). Blockchain technology and its relationships to sustainable supply chain management. *Int. J. Prod. Res.* 57, 2117–2135. doi: 10.1080/00207543.2018.1533261

Sadiq, M. B., and Anal, A. K. (2023). *Improving traceability in the food supply chain management system. Pandemics and innovative food systems*. Boca Raton, FL: CRC Press.

Samadhiya, A., Kumar, A., Agrawal, R., Kazancoglu, Y., and Agrawal, R. (2023). Reinventing reverse logistics through Blockchain technology: a comprehensive review and future research propositions. *Supply Chain Forum* 24, 81–102. doi: 10.1080/16258312.2022.2067485

Sharma, P., Jindal, R., and Borah, M. D. (2022). A review of smart contract-based platforms, applications, and challenges. *Clust. Comput.* 26, 395–421. doi: 10.1007/s10586-021-03491-1

Singh, P., Holm, K., Beliatis, M. J., Ionita, A., Presser, M., Wolfgang, P., et al. (2022). "Blockchain for economy of scale in wind industry: a demo case" in *Lecture notes in computer science (including subseries lecture notes in artificial intelligence and lecture notes in bioinformatics)*. eds. A. González-Vidal, A. Mohamed Abdelgawad, E. Sabir, S. Ziegler and L. Ladid (Arizona: Arizona State University)

Singh, R. K., and Vishwakarma, L. P. (2022). "Application of Blockchain Technology in Agri-Food Supply Chains: opportunities and challenges" in *Blockchain in a volatile-uncertain-complex-ambiguous world*. eds. K. Mathiyazhagan, V. R. Sreedharan, D. Mathivathanan and M. V. Sunder (Amsterdam, Netherlands: Elsevier), 101–117.

Song, W. (2020). Research on Blockchain for sustainable E-agriculture. In: *2020 IEEE Technology and Engineering Management Conference, TEMSCON 2020*. Institute of Electrical and Electronics Engineers Inc.

Song, C., and Li, C. (2021). Research on agricultural products supply chain traceability system: Blockchain consensus algorithm optimization. In: *2021 9th International Conference on Traffic and Logistic Engineering, ICTLE 2021*. Institute of Electrical and Electronics Engineers Inc, pp. 64–68.

Sundarakani, B., Ajaykumar, A., and Gunasekaran, A. (2021). Big data driven supply chain design and applications for Blockchain: an action research using case study approach. *Omega* 102:102452. doi: 10.1016/j.omega.2021.102452

Treiblmaier, H. (2019). Toward more rigorous Blockchain research: recommendations for writing Blockchain case studies. *Front. Blockchain* 2, 1–15. doi: 10.3389/fbloc.2019.00003

Valencia-Payan, C., Grass-Ramírez, J. F., Ramirez-Gonzalez, G., and Corrales, J. C. (2022). A smart contract for coffee transport and storage with data validation. *IEEE Access* 10, 37857–37869. doi: 10.1109/ACCESS.2022.3165087

Westerkamp, M., Victor, F., and Küpper, A. (2020). Tracing manufacturing processes using Blockchain-based token compositions. *Digit Commun Netw* 6, 167–176. doi: 10.1016/j.dcan.2019.01.007

Wünsche, J. F., and Fernqvist, F. (2022). The potential of Blockchain Technology in the Transition Towards Sustainable Food Systems. *Sustainability (Switzerland)* 14:739. doi: 10.3390/su14137739

Yogarajan, L., Masukujjaman, M., Ali, M. H., Khalid, N., Osman, L. H., and Alam, S. S. (2023). Exploring the hype of Blockchain adoption in Agri-food supply chain: a systematic literature review. *Agriculture (Switzerland)* 13, 1–24. doi: 10.3390/agriculture13061173

Zhu, Q., and Kouhizadeh, M. (2019). Blockchain technology, supply chain information, and strategic product deletion management. *IEEE Eng. Manag. Rev.* 47, 36–44. doi: 10.1109/EMR.2019.2898178

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Edible plants as a complement to the diet of peasant farmers: a case study of the Totonacapan region of Puebla, Mexico

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Peasant societies have traditionally produced food for themselves and for the market based on a diversity of plants that they grow and cultivate in their agroecosystems; however, these societies are modifying their agriculture, their consumption, the structure and composition of their plots and abandoning the consumption of these species, which are gradually ceasing to be part of their diets. This research aimed to analyze the contribution of local crop diversity to the peasant diet of the Totonacapan region of Puebla, Mexico. During 2020, 270 dietary surveys were applied, and in 2022, the richness of edible species in 146 peasant plots was recorded and 69 semi-structured interviews were conducted to document ethnobotanical information on edible species. A total of 102 edible species were identified in the plots; 65 are native and 37 are introduced. The milpas and the family garden are the main areas where food for self-consumption is grown: corn, beans, and some grean leaves (*quelites*). Meanwhile, coffee plantations and horticultural areas mainly contain food for sale; coffee, fat pepper, bananas, oranges, and chili peppers stand out. Half of the plants inventoried (53%) were not recorded in the diet surveys. Absent foods were fruit trees, roots and tubers, spices, *quelites*, and local vegetables. On the other hand, most of the 48 species recorded in the plots and the dietary surveys had a very low frequency of consumption. The limited consumption of this group of species is largely because they are no longer suitable for consumption, are difficult to cook, or require much time for collection and preparation. The reason villagers conserve these plants may be because they are emergency foods. After all, they consume them eventually or in times of scarcity, hence the importance of keeping them in the plots. Even though a great wealth of edible plants is grown in the campesino plots, it does not mean they have a relevant presence in the diets.

KEYWORDS

agrodiversity, farmer plots, self-consumption, Totonacs, traditional food

Introduction

Small-scale and peasant agriculture can contribute to an improvement in the nutrition of the population in underdeveloped countries, characterized by high agricultural diversity with the potential to solve malnutrition problems (Frison et al., 2006; Lachat et al., 2018). In some regions, such as in several African countries, it is well recognized that agrodiversity, including wild and cultivated plants, is indispensable for achieving food security and food sovereignty in indigenous smallholder communities (Hassen, 2021; Koukou et al., 2022). Access to agrodiverse foods can have a positive impact on the nutritional quality of the population's diet: the inclusion of fruits, flowers, leaves, stems and tubers (among others) of diverse species facilitates the acquisition of micronutrients, such as vitamins, minerals and essential oils, quality macronutrients (unrefined carbohydrates, containing dietary fiber and water) in addition to facilitating a functional diet (Aragaw et al., 2021) by increasing the consumption of foods containing elements that are known to possess preventive or regulatory properties against various illnesses (Grivetti and Ogle, 2000). Despite this importance, there is little knowledge of the consumption of these plant species whose diverse natural wealth and autochthonous knowledge are safeguarded by a plethora of rural and indigenous communities.

Many ethnobotanical studies discuss the richness of edible species in rural and peasant farming regions, but few study the frequency of their consumption. In Mexico, the cultural, economic, and ecological importance of approximately 2,168 edible plant species found predominantly in indigenous and rural areas has been documented (Mapes and Basurto, 2016); however, there are no records regarding their use (Neupane et al., 2022). Therefore, there is a need for more studies that evaluate the extent to which local agrobiodiversity on smallholdings complements peasant diets, given that a high richness of edible species on farm plots does not necessarily imply that they are being consumed frequently (Soto-Pinto et al., 2022). Many wild or fostered edible plant species are generally considered as emergency food sources, consumed in times of scarcity or when there is a chronic shortage of staple foods such as maize (Mapes and Basurto, 2016; Rivera-Núñez et al., 2022); however, their consumption when staple foods (mainly cereals) are sufficient is not known. Furthermore, several studies report that in some rural regions, the consumption of fruits and vegetables is limited as the vast majority are sold to supplement household income; therefore, they are no longer an integral component of household self-subsistence (Miller et al., 2016; Mehraban and Ickowitz, 2021). In the case of *quelites* (edible wild herbs or greens), many species are reported (Bye and Linares, 2000); however, only 50% form part of the diet of peasant families (Basurto-Peña, 2011).

Knowledge of the extent to which local agricultural diversity is exploited and what limits its use among communities, particularly native peoples, would enable us to provide guidelines and focus efforts on promoting edible plants, as many people and institutions propose. The prevailing idea at the international and national level is that plants that are underutilized should be promoted to improve the nutrition of the world population (Knez et al., 2023); however, there is a lack of data that would assist us in the decision-making process regarding the form and process such promotion would take and on which food groups efforts should be concentrated. This concept occurs within the recent context of dietary changes as a result of increased rural–urban migration, urbanization, the widespread incorporation of industrialized foods into the diets of a large part of the population, changing tastes of new generations, and the increased perception that local foods are consumed only by poor families (Kuhnlein and Receveur, 1996; Duguma, 2020; Soto-Pinto et al., 2022).

This study provides data on the frequency of consumption of locally produced foods in the diets of an indigenous group that knows the consumption of such plants, both currently and historically (Basurto-Peña et al., 1998; García-Vazquez et al., 2022). The research was conducted in the Totonacapan region, situated in the northeastern part of the state of Puebla. The area is inhabited by the Totonac people, who speak one of the 68 native languages of Mexico [INALI (Instituto Nacional de Lenguas Indígenas), 2010] and descend from an ancient Mesoamerican people (González-Bonilla, 1942). Before colonization, the Totonaca population based their diet on the use of a great diversity of plants. Many of them were also important in ceremonies, rituals, and traditional medicine, and some had their domestication center in Totonacapan, which is the emblematic case of vanilla (Bruman, 1948; Kelly and Palerm, 1952). Several ethnobotanical studies have reported that the Totonacs recognize about 200 species of edible plants (Martínez-Alfaro et al., 1995, 2007; Basurto-Peña et al., 1998, 2003), including herbs, greens, seeds, fruits, vegetables, tubers, and roots. However, although many edible plants are grown on the plots, families rely more on the market to feed themselves (Espinoza-Pérez et al., 2023). As the region is predominantly mountainous, the agricultural landscape of the Totonacapan region consists of steep slopes (>30%) and valleys. It is characterized by a mosaic of agricultural areas and *acahuales* (fallow land colonized by secondary vegetation). Agricultural areas are recognized according to the preeminence of certain crops: maize, coffee, beans, chili, and sugarcane. Against this background, this study aims to analyze the use of the diversity of edible plants that are found on smallholder farms and as an integral part of the peasant farmer diet, grounded on the following research question: To what extent is the richness of edible plants consumed by farming families who know their use and the floristic resource in their region?

Materials and methods

Study background

Based on 270 surveys carried out in 2020, a study was published on the diet of peasant farmers in the poblano Totonacapan region in which it was reported that the diet of these families included around 159 food items, comprising 104 edible plants, of which 63 originated from the family plots, and 41 were purchased externally. As mentioned, we only worked with peasant families and did not include families that were dedicated to other activities, for example, livestock farmers or had other occupations such as carpenters, construction workers, and chauffeurs. All the families interviewed follow a Mesoamerican diet; that is, they continue to consume corn, beans, chili pepper, *quelites*, *chayotes* (*Sechium edule*), squash, and other local vegetables. Differences in diets between families were reported, with some consuming more self-subsistence foods and others relying more on the market. According to the statistical tests performed in the previous study, factors such as income and environment did not influence food availability. From the previously mentioned research, four dietary profiles were identified and grouped according to the frequency of consumption and the origin of the food (A, B, C, and D) (Espinoza-Pérez et al., 2023). Households in groups A and D consumed more frequently self-produced and locally produced foods (corn, beans, chili pepper, local vegetables) were named regional food groups. In addition, families in group D included complementary foods such as *quelites* and other additional species of beans in their diet. In the field, we observed that these families spend more time cultivating their plots and place greater value on the consumption of local plants and crops. In contrast, the regional transition food group (groups B and C) consumed more externally sourced foods, including corn, beans, chili peppers, and other vegetables. The difference between the two groups was that the families in group C consumed tortillas from *tortillerías* (tortilla shops) and no longer homemade tortillas, as in group B, although with purchased corn. Because of this situation, these families had low consumption of local food, which includes own-produced food and food produced at the local or community level (Espinoza-Pérez et al., 2023).

Records of edible species

From the 270 surveys mentioned above, two families were randomly selected from each dietary profile in nine localities distributed over seven municipalities within the Poblano Totonacapan region (Table 1), giving us a total of 69 families. In each selected household, we produced an inventory of the richness of edible species in each agroecosystem (milpa, coffee plantation, home garden, horticulture, and *acahual*). These agroecosystems are different in structure and floristic composition and differ in management. A total of 146 plots were sampled: 63 milpas (cornfields), 47 coffee plantations, 27 home gardens, seven horticulture plots, and two sites that were *acahual* (fallow land). In Mexico, we call milpa the traditional agricultural system made up of a polyculture, its main species is corn, accompanied by various species of beans, pumpkins, chili peppers, tomatoes, and many other edible plants. The surface area devoted to cultivation was recorded in each plot. The "walk in the agroecosystems" technique (Phillips and Gentry, 1993), which consists of walking throughout the plots with the owner and recording herbs, vines, shrubs, and trees, was used. To ensure that most of the edible plants were recorded, the visits were conducted during the period between sowing and harvest. For example, the milpa agroecosystem was surveyed between January and June while the horticultural areas from May to July and from September to October, corresponding to the growing periods; the remaining agroecosystems (coffee plantation, home garden, *acahual*) were visited throughout the year as there is no specific period when these are managed and cultivated.

TABLE 1 Number of families surveyed and type of climate for each locality.

Municipality	Locality	NF	Climate
Atlequizayan	Ignacio Allende	8	A(f)
Zapotitlán de Méndez	Tuxtla	8	A(f)
	Nanacatlán	8	A(f)
Olintla	Vicente Guerrero	8	A(f)
	Dimas López	8	A(f)
Jonotla	Ecatlán	8	A(f)
Camocuautla	Tapayula	7	(A)C(fm)
Amixtlán	Cuautotola	8	(A)C(fm)
Huehuetla	Ozeloanacaxtla	6	(A)C(fm)

A(f): warm wet climate; (A)C (fm): warm subhumid climate; NF: number of families in each locality that participated in the study.

For each edible plant identified, the name in Totonac and Spanish was recorded, as well as parts of the plant used, management, and destination of the edible products (self-consumption, sale, or both) (Soto-Pinto et al., 2022). In addition, the reasons for occasional consumption or abandonment of plant consumption in the diet were explored through semi-structured interviews with the participating families who owned the inventoried plots. Information on the origin and life cycle of the plants was reviewed in the literature. Each plant was recorded in a database and classified into cereals, herbs and leafy greens, fruits, vegetables, legumes, roots and tubers, spices, beverages, and seeds (Kennedy et al., 2013; Figure 1).

Data analysis

A database was generated in Excel 2013® and then transferred to the statistical program SPSS 21.0 to determine the frequency of species for each household, origin, food group, management type, and agroecosystem. The relative frequency of each plant species was also calculated for each household. From the diet surveys applied in 2020, the consumption frequency per week (F) of the plants recorded in the plots was calculated using the following formula:

$$F = \left(Q^{*}S\right) / E.$$

where F = consumption frequency per week.
Q = total consumption frequency reported by food or component.
S = number of days consumed per week.
E = number of survey days.

Finally, a Kruskal–Wallis test was performed on the edible species richness data to identify possible significant differences in the use and consumption of edible plants between food profiles and by agroecosystem, using the SPSS 21.0 statistical program.

Results

Richness and distribution of edible plant species

At the regional level, 102 edible species were identified of which 65 were native species and 37 introduced species, belonging to nine food groups. According to the level of human intervention, 57 species were cultivated, 31 enhanced, and 13 collected. These plants are distributed in five agroecosystems (milpa coffee plantations, home gardens, horticultural areas, and *acahuales*) that provide food for peasant households (Table 2). The coffee plantations contained 71 edible plants, home gardens 66, milpa 57, horticulture plots 13, and *acahuales* 8. The food groups with the highest number of species were fruit trees (32), herbs and leafy greens (26), and local vegetables (20) (Table 3). Agroecosystems are different in their composition and floristic structure. In milpas and horticulture it is common to observe an association of herbaceous plants, some shrub species, and very few tree species. On the contrary, a tree stratum predominates in coffee plantations and *acahuales*. On the other hand, the home garden is a space where all types of plants are associated, from

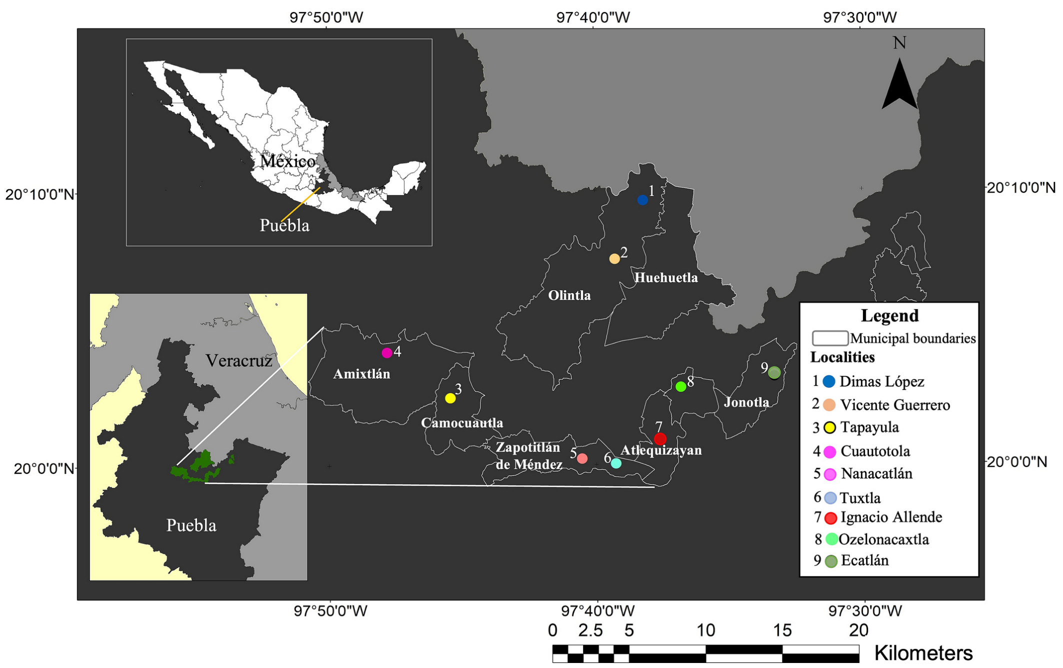

FIGURE 1
Geographical location and distribution of study sites in the Totonacapan region of Puebla, Mexico.

herbaceous, shrub and tree species, and it is a space managed mainly by women.

Edible species by food group and agroecosystem

Edible species richness data showed differences between families, food profiles, and agroecosystems. A mean of 13.8 ± 7.05 edible species per family was recorded at the regional level. Families in profile groups A and D (16.05 ± 6.01; 19.29 ± 9.22) presented a significantly higher richness of edible plants than those in groups B and C (9.81 ± 2.68; 10.16 ± 3.46). Homegardens and coffee plantations presented a higher mean plant richness (8.25 ± 4.95; 7.7 ± 5.7) than the other agroecosystems. This high richness is because both agroecosystems are cultivated most of the year. On the other hand, milpa and horticulture are cultivated seasonally, and the richness of plants that can be found varies from year to year. *Acahual* is a partially abandoned system, only edible plants are harvested, and it does not receive intensive management like the other agroecosystems. As can be observed, almost all families cultivated milpa (63 families out of a total of 69), and the majority cultivated coffee (47 families out of 69). Slightly less than half of the families possessed an orchard (27 out of 69), and a small number possessed a horticultural area or *acahual* (Table 4).

Consumption of edible species present in the farm plots

Of 102 edible species recorded, 37 were used exclusively for self-consumption, 52 for self-consumption and sale, and 13 for sale only. In addition, 54 species were not recorded in the diet surveys, while 48 were recorded. According to those interviewed, of the 54 species absent from the diet survey, 28 are used for self-consumption, 17 for self-consumption and sale, and a few are exclusively for sale (9 species). The majority were fruit species (25 species), 11 species of leafy greens, eight species of local vegetables, and four species belonging to the tubers and roots group. Most of the species were cultivated and encouraged, 25 and 20 species, respectively, (Table 5).

Regarding the edible plant species recorded in the dietary surveys and farm plots, in addition to the staple food crop maize and six species of beans, there were seven species of fruits, 11 species of vegetables, and 17 species of *quelites*. Of these, 33 were cultivated, 11 encouraged. As for their destination, 35 species were used for self-consumption and four were exclusively for sale: coffee, allspice, bananas, and oranges (Table 5). Coffee and allspice are agricultural products that are marketed outside the region. At the same time, bananas and oranges are sold in the same communities.

The distribution of edible plants recorded in dietary surveys differs greatly from those not recorded. Most plants recorded in the diet survey were more abundant than unrecorded species in the corresponding farm plots; however, some unrecorded species, such as *chalahuite*, *mamey sapote*, *capulin*, peach, mango, and *tequelite*, were common in the plots. Of the plants recorded in the diet survey, 40 out of 48 species were present in more than five plots, and only three species were found in two or fewer plots (Figure 2B); in contrast, unrecorded species presented a very low frequency in the plots, with only six out of 54 species present in five or more plots and a large number found in only two or less (Figure 2A). The most frequent crops recorded in the plots were maize and coffee, followed by bananas, oranges, *majayan* beans, *chayote*, chili, *huaxi*, allspice, *xkijit* (*Renealmia alpinia*), and some *quelites* such as elephant ear and citrus

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TABLE 2 List of edible species present in the plots of peasant families in the Totonacapan region of Puebla.

Food group	Scientific name	Common name		Relative frequency (%)	Consumption frequency (Times per week)	Life cycle	Origin	Part of plant used	Agroecosystem	Management
	Species	Spanish name	Totonac							
Beverages	*Coffea arabica* L.	Café	Kapen	6.2	7	2	2	5	1,2	1
	Coffea canephora L.	Café de árbol	Kapen	0.1	0	2	2	5	2	1
	Cymbopogon citratus (DC) Stapf.	Zacate limón	Sekget'kapen	0.2	0.5	3	2	3	3	1
Cereal	*Zea mays* L.	Maíz	Kuxi	6.6	12	2	1	5	1	1
Spices	*Pimenta dioica* (L.) Merr.	Pimienta gorda	Ukum	2.8	0.5	1	1	5,3	2,3	1
	Sesamum indicum L.	Ajonjolí	Talhtsinkiw	0.1	0.5	3	2	6	4	1
	Vanilla planifolia (Jacks.)	Vainilla	Sumixanat	0.2	0	3	1	5,7	2	1
	Vanilla insignis Ames	Vainilla	Sumixanat	0.2	0	3	1	5	2	1
	Vanilla pompona Schiede.	Vainilla	Sumixanat	0.2	0	3	1	5,7	2	1
Fruit	*Ananas comosus* (L.) Merr.	Piña	Akaxka´	0.1	0	3	2	5	3	1
	Annona cherimola Mill.	Chirimoya	Akchitkiwi'	0.3	0	1	2	5	2	1
	Annona muricata L.	Guanábana	ND	0.1	0	1	1	5	2	1
	Artocarpus heterophyllus Lam.	Yaca	ND	0.1	0	1	2	5	2,3	1
	Carica papaya L.	Papaya	Papaya	0.6	0.5	2	1	5	2,3	1
	Citrus ×latifolia (Yu. Tanaka) Tanaka	Limón persa	Xukut	0.1	0	2	2	5	2	1
	Citrus ×sinensis (L.) Osbeck	Naranja	Laxux	4.2	0.5	1	2	5	2,3	1
	Citrullus lanatus (Thunb.) Matsum. & Nakai	Sandía melón	ND	0.1	0	3	2	5	2	1
	Citrus x aurantifolia (Christm.) Swingle	Lima	Tsikit'lima	0.1	0	1	2	5	3	1
	Citrus reticulata Blanco	Mandarina	Mandarina	1.7	0.5	1	2	5	2,3	1
	Citrus ×limon (L.) Burm. f.	Limón	Limón	1.0	0.5	1	2	5	1,2	1
	Conostegia xalapensis (Bonpl.) D. Don ex DC.	Capulin	Mujut	1.3	0	2	1	5	1,5	2
	Couepia polyandra (Kunth) Rose	Olopillo	Pija	0.1	0	1	1	5	3,5	3
	Diospyros nigra (J. F. Gmel.) Perr.	Zapote negro	Suwalh	0.5	0	1	1	5	1,2	2
	Inga vera Willd.	Chalahuite	Kalama	2.8	0	1	1	5	2	2
	Licania platypus Hemsl.	Zapote cabello	Akgchixitjaka'	0.5	0	1	1	5	2,5	3
	Litchi chinensis Sonn.	Lichi	Lichi	0.2	0	1	2	5	2	1
	Macadamia spp.	Macadamia	Macadamia	0.3	0	2	2	5	2	1
	Mangifera indica L.	Mango	SD	1.1	0	1	2	5	2,5	2
	Musa spp.	Plátano	Seekgna'	6.4	0.5	2	2	5	1,2,3	1

(Continued)

Food group	Scientific name: Species	Common name: Spanish name	Common name: Totonac	Relative frequency (%)	Consumption frequency (Times per week)	Life cycle	Origin	Part of plant used	Agroecosystem	Management
	Parathesis psychotrioides L.	Capulin	Akgtalaawat	0.4	0	2	1	5	1,5	2
	Parmentiera aculeata (Kunth).	Chote	Puxni	0.1	0	1	1	5	3	2
	Passiflora edulis Sims	Maracuya	Maracuya	0.1	0	3	2	5	2,3	1
	Pouteria sapota (Jacq.) H. E. Moore & Stearn	Zapote mamey	Jaka	2.2	0	1	1	5	3,5	3
	Prunus persica (L.) Batsch	Durazno	Tarazno	1.4	0	1	2	5	1,3	1
	Psidium guajava L.	Guayaba	Asiwit	1.3	0.5	1	1	5	2, 3	1
	Punica granatum L.	Granada	SD	0.1	0	1	2	5	3	1
	Saccharum officinarum L.	Caña	Chankat	1.3	0.5	2	2	2	1,2,3,6	1
	Selenicerius sp.	Pitahaya	Chach	0.3	0	3	1	5	2,3,5	3
	Spondias mombin L.	Jobo	Xiipa	0.1	0	1	1	5	2,5	3
	Syzygium jambos (L.) Alston	Pomarosa	Pumarrosa	0.1	0	1	2	5	2,5	2
	Theobroma cacao L.	Cacao	Cacao	0.1	0	1	1	5	2	1
Leguminous plants	*Arachis hypogaea* L.	Cacahuate	Cacawatl	0.4	0	3	2	1	4	1
	Cajanus cajan (L.) Huth	Frijol de árbol	Kiwi'stapu	0.1	0	3	2	5	1	2
	Leucaena leucocephala L.	Huaxi	Lilekg	2.9	0.2	1	1	5,6	1,2,3	1
	Phaseolus coccineus L.	Frijol ayocote	Tlanka'stapu	0.5	0.2	3	1	5,6	1,3	1
	Phaseolus dumosus Macfad.	Frijol xoyoma	Xuymit	0.8	0.2	3	1	5,6	1,3	1
	Vicia faba L.	Haba	Aux	0.6	0.2	3	2	5,6	1	1
	Vigna unguiculata L.	Frijol torito	Lukut'stapu	1.3	0.2	3	2	5,6	1,3	1
	Phaseolus vulgaris L.	Frijol enredadera	Majayan	3.8	1	3	1	5,6	1,3,4	1
Quelites/ herbs and leafy greens	*Amaranthus hybridus* L.	Quintonil blanco	Kgalhtunit	0.1	0.12	3	1	3	3,4	1
	Amaranthus hypochondriacus L.	Quintonil rojo	Kgalhtunit	1.8	0.12	3	1	3	3, 4	1
	Arthrostemma ciliatum Pav. ex D. Don	Agrio cuadrado	Xalhtakaka'xkutna'	0.2	0.12	3	1	3	1,2,3,5	3
	Allium neapolitanum Cirillo	Cebollina	Kgatsasna	2.1	0.12	3	2	3	1,3	1
	Begonia heracleifolia Cham.	Agrio rayada	Xalpilili'xuktna'	2.1	0.12	3	1	2	1,2,3,5	3
	Begonia nelumbiifolia Cham. Et	Agrio	Sturonkgot	0.9	0.12	3	1	2,3	1,2,3,5	3
	Cyclanthera langaei Cong.	Cincoquelites	Tatsilum/Akgawa'	2.1	0.12	3	1	3	1,2,3	2
	Cyclanthera ribiflora (Schltdl.) Cogn.	Quelite torito	Xkulum	0.6	0.12	3	1	3	1,2,3	2
	Coriandrum sativum L.	Cilantro	Kulanto	1.0	0.12	3	2	3	4	1

(Continued)

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TABLE 2 (Continued)

Food group	Scientific name	Common name		Relative frequency (%)	Consumption frequency (Times per week)	Life cycle	Origin	Part of plant used	Agroecosystem	Management
	Species	Spanish name	Totonac							
	Erythrina caribaea Krukoff & Barneby	Gásparo	Lalhni'	1.1	0.12	1	1	3,4	1,2,3,5	2
	Ipomoea dumosa (Benth.) L. O. Williams	Manto blanco	Siiyu'	0.1	0.12	3	1	3	2,3	2
	Mentha spicata L.	Hierba buena	Kuxlalhkgejna'	0.5	0.12	3	2	3	3	1
	Porophyllum ruderale (Jacq.) Cass	Papaloquelite	Puksnankak	1.0	0.12	3	1	3	3,4	1
	Rumex crispus L.	Lengua de vaca	Skgota	0.7	0.12	3	2	3	3	2
	Solanum americanum Mill.	Hierba mora	Mustulut	3.7	0.12	3	1	3	1,2,3,4	2
	Xanthosoma robustum Schott	Barabarón	Pa'xnikak	2.2	0.12	3	1	3	1,2,5	2
	Yucca aloifolia L.	Equizote	Akalukut	1.3	0.12	2	1	4	5	3
	Begonia incarnata Link & Otto	Ala de ángel	Xuktna'	0.1	0	3	1	2	3	3
	Begonia thiemei C. DC.	Agrio extranjero	Extranjero	0.1	0	3	1	2,3	1,2,3,5	3
	Cnidoscolus multilobus (Pax) I. M. Johnston	Mala mujer	Kgajni	0.2	0	2	1	4,6	5	3
	Eryngium foetidum L.	Cilantro extranjero	Lhtukuni'kulanto	0.1	0	3	1	3	2,3	2
	Dysphania ambrosioides (L.) Mosyakin & Clemants	Epazote	Lhkgejna	0.3	0	3	1	3	3	1
	Jaltomata procumbens (Cav.) J. L. Gentry	Quelite cimarrona	ND	0.1	0	3	1	3	3	3
	Peperomia maculosa (L.) Hook.	Tequelite	Kuksasan	0.6	0	3	1	3	1,2,3	1
	Peperomia peltilimba C.DC.	Tequelite chiquito	Laktsu kuksasan	0.2	0	3	1	3	2,3	1
	Physalis gracilis (Miers)	Tomatillo	Chapululh	0.1	0	3	1	3	1,2,3	2
	Smilax laurifolia L.	Cozol	Kgentsililh	0.3	0	3	1	2	2,4	3
	Tinantia erecta (Jacq.) Schltdl.	Pata de gallo	Kitxtak	0.3	0	3	1	3	2,3	2
Seeds	*Jatropha curcas* L.	Piñon	Chuu'ta	0.8	0.5	2	1	6	2,3	1
Tubers/ Roots	*Dioscorea alata* L.	Ñame	Tlitlee'kglh	0.1	0	3	1	1	2,3,5	2
	Dioscorea bulbifera L.	Papa voladora	Pabs	0.4	0	3	1	1	1,2	3
	Ipomoea batatas (L.) Lam.	Camote	Manta	0.1	0	3	1	1	1,2,3	2
	Manihot esculenta Crantz	Yuca	Koxkgew	0.4	0	2	2	1	2,3	1
	Xanthosoma sagittifolium (L.) Schott	Mafafa	Pisis	0.2	0.5	3	1	1	1,2	2

(Continued)

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TABLE 2 (Continued)

Food group	Scientific name	Common name		Relative frequency (%)	Consumption frequency (Times per week)	Life cycle	Origin	Part of plant used	Agroecosystem	Management
	Species	Spanish name	Totonac							
Local vegetables	*Allium cepa* L.	Cebolla morada	ND	0.1	0	3	2	1	4	1
	Beilschmiedia anay (S.F.Blake)	Anaya	Aniya	0.1	0	1	1	5	2,5	3
	Brassica oleracea var. *capitata* for. Alba subv. Conica	Col de hoja	Kulx	0.1	0	3	2	3	4	1
	Capsicum annuum spp.	Chile de árbol, serrano, bolita	Stilampin	3.1	1.5	3	1	5,6	1,2,3,4	1
	Capsicum annuum var. glabriusculum	Chiltepin	Laktsuupi'n	2.2	1.5	3	1	5,6	2,3	1
	Cucurbita sp.	Calabaza	Nipxi	1.9	0.3	3	1	4,5	1,2,3	1
	Cucurbita ficifolia Bouché	Chilacayote	ND	0.2	0.3	3	2	5	1	1
	Lycopersicon esculentum P. Mill.	Jitomate riñon	Xtili'pakglhcha	1.1	0.3	3	2	5	1,3,4	1
	Lycopersicon lycopersicum (L.) H. Karst.	Jitomate silvestre	Staku'pakglhcha	0.4	0.3	3	2	5	1,3	1
	Persea americana Mill.	Aguacate criollo	Kukuta	0.8	0.3	1	1	5	2,3	2
	Persea schiedeana Nees.	Pahua	Lhpuj	1.3	0.3	1	1	5	3,5	2
	Physalis ixocarpa Brot. ex. Horn.	Tomate de cáscara	Tamat	0.4	0.3	3	1	5	4	1
	Renealmia alpinia (Rottb.) Maas	Jengibre de jardín	Xkijit	2.6	0.3	2	1	3,5	2	2
	Sechium edule (Jacq.) Sw.	Chayotes	Maklhtukun	3.3	0.3	3	1	1,3,5	1,2,3	1
	Cucurbita argyrosperma C. Huber	Pipian	Talhtsi	0.1	0	3	1	4,5	1	1
	Opuntia cochenillifera (L.) Mill.	Nopal	Axilh	0.4	0	2	1	2	2,3	2
	Persea americana var. *americana*	Aguacate	Kukutlitli	0.1	0	1	1	5	3	2
	Renealmia mexicana Klotzsch ex. Petersen	Xkijit	Sikulna xkjit	0.1	0	2	1	3,5	2	2
	Solanum suaveolens Kunth & C.D. Bouché	Tomate de monte	Sipi'tomat	0.2	0	3	2	5	2,3	3

Plant type: (1) tree, (2) bush, (3) herbaceous; Origen: (1) native, (2) introduced; Part of plant used: (1) root, tuber, rhizome, (2) stems, (3) leaves, (4) flowers or inflorescence, (5) fruit, (6) seeds, (7) sap; Agroecosystem: (1) milpa, (2) coffee plantation, (3) homegarden, (4) horticulture, (5) acahual; Management: (1) cultivated; (2) fomented; (3) collected/wild; ND = No data.

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TABLE 3 Edible species richness by food group and agroecosystem.

Food group	Milpa	Coffee plantation	Homegarden	Horticulture	*Acahual*	Species richness (unique)
Beverages	2	2	2	0	1	3
Cereals	1	0	1	0	0	1
Spices	3	3	5	1	0	5
Fruit	14	25	23	1	2	32
Leguminous plants	7	3	5	2	0	8
Herbs and leafy greens	14	21	16	5	3	28
Seeds	1	1	1	0	0	1
Tubers/Roots	3	5	2	0	0	5
Vegetables	12	11	11	4	2	19
Number of Species	57	71	66	13	8	102

TABLE 4 Richness of recorded edible plants between families, dietary profiles, and by agroecosystem.

	Edible plant richness	
	Mean	Standard deviation
Household ($n = 69$)	13.8	±7.1
Profiles*		
A ($n = 18$)	16.1[b]	±6.1
B ($n = 16$)	9.8[a]	±2.6
C ($n = 18$)	10.1[a]	±3.4
D ($n = 17$)	19.2[b]	±9.2
*Agroecosystem***		
Milpa ($n = 63$)	5.2[ab]	±2.8
Coffee plantation ($n = 47$)	7.7[b]	±5.7
Homegarden ($n = 27$)	8.2[b]	±4.9
Horticulture ($n = 7$)	3.8[a]	±2.4
Acahual ($n = 2$)	4.5[a]	±0.7

*Kruskal–Wallis test gl: 3, $p \leq 0.01$. **Kruskal–Wallis test, gl: 4, $p \leq 0.01$. ab = means with the same letters between profiles (A–D) and agroecosystem are not statistically different ($p \leq 0.01$).

TABLE 5 Number of edible plants present in the farm plots that were recorded or unrecorded in the diet surveys.

Food group	Recorded in the diet surveys		
	No	Yes	Total
Cereals	0	1	1
Beverages	1	2	3
Fruit	25	7	32
Spices	3	2	5
Leguminous plants	2	6	8
Quelites (herbs and leafy greens)	11	17	28
Roots and tubers	4	1	5
Seeds	0	1	1
Local vegetables	8	11	19
Management			
Collected	9	4	13
Encouraged	20	11	31
Cultivated	25	33	58
Destination			
Self-consumption	28	9	37
Self-consumption and sale	17	35	52
Sale	9	4	13

fruit. The remaining species in Figure 3B were reported in less than 15 of the 69 households.

Differentiated consumption of edible plants

Among the four dietary profiles, there were significant differences in the species richness recorded in the agricultural plots. To differentiate between them, we will call them groups A, B, C, and D. In this case, groups A and D had more edible species than groups B and C (Figure 3). Thus, the families that followed a diet in which there was a high consumption frequency of self-produced and local/regional food (groups A and D) showed a higher richness of edible species in their plots compared to families that demonstrated a higher consumption frequency of purchased food (groups B and C). The families of profiles A, B, and C had a high proportion of plants inventoried in the agroecosystems and not documented in the diets. Among the same groups of families, no significant differences were observed in the consumption of edible plants from the plots and those recorded in the diet surveys. In families of profile D, 50% of the edible plants found in their agroecosystems were included in their diets, maintaining a more diversified diet with food from their plots than the other three groups (Figure 3).

Low consumption frequency of local edible species

When asked about the reasons for the low consumption frequency of edible species, respondents stated that it was due to the loss of

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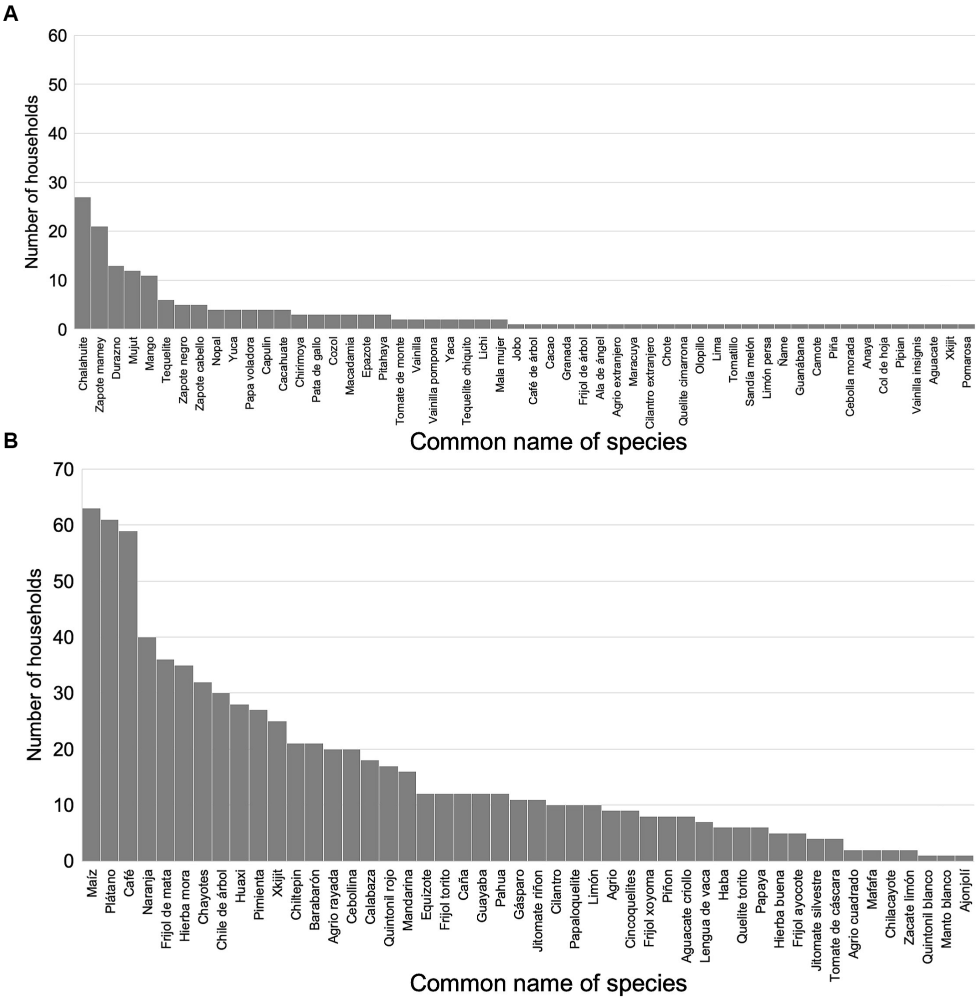

FIGURE 2
(A) Frequency of edible species present in the plots but unrecorded in the diet surveys. **(B)** Frequency of edible species present in the plots and recorded in the diet surveys.

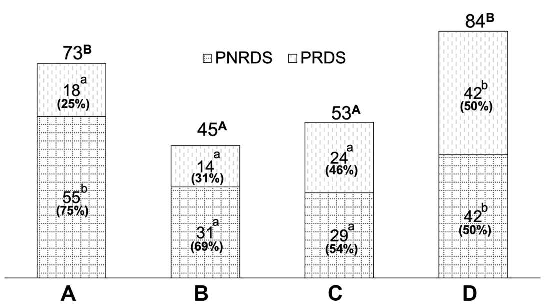

FIGURE 3
Richness of edible plants recorded in the agroecosystems but not in dietary surveys (PNRDS), and edible plants recorded in both agroecosystems and dietary surveys (PRDS) by dietary profile. **Kruskal–Wallis test, gl: 3, $p \leq 0.01$. ab = means with the same letters within groups **(A–D)** are not statistically different. AB = means with the same capital letters among groups are not statistically different.

traditional autochthonous knowledge related to the cultivation and use of edible plants. Furthermore, they indicated that some plants are difficult to cook, are not popular in diets, receive little promotion, and are rarely cultivated. In addition, they emphasized that new generations are more disconnected from their natural surroundings and agroecosystems than previous generations, which is reflected in the decreasing consumption of locally produced food (Figure 4). Respondents also mentioned that the collection of some herbs and *quelites* is time-consuming, time that most families cannot afford, thus impeding their consumption and cultivation. Such plants include *quelites*: *Cyclanthera langaei*, *Cyclanthera ribiflora*, *Ipomoea dumosa*, and the flowers of the *Cnidoscolus multilobus*. A quarter of the 69 families surveyed commented that their children no longer want to consume *quelites*, as some plants have a bitter taste and burn the tongue; such is the case of *Xanthosoma robustum*, *Solanum americanum*, and *Physalis gracilis*. In addition, 20% of the families surveyed stressed that many *quelites* are no longer being promoted or cultivated and are currently difficult to find in the local market or in the areas where they used to collect them. Respondents also commented that the collection and preparation of *Dioscorea alata* and *Manihot esculenta* is also time-consuming. In contrast, fruits do not require much preparation; however, many species are not encouraged or cultivated. This is the case *Acanthocereus tetragonus*, *Annona muricata*, *Spodias mombin*, *Moquilea platypus*, *Pouteria sapota*, and *Syzygium jambos*, which were present in five or fewer plots out of the

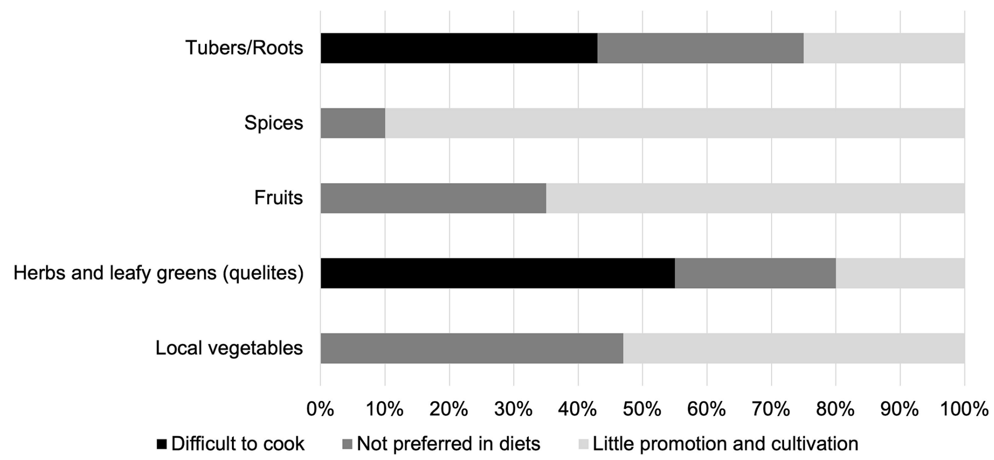

FIGURE 4
Reasons given by households for the low consumption frequency of several food groups. For the analysis, the vegetable group did not include chili, tomato, and squash. n: 69.

146 inventoried. Regarding local vegetables and spices, respondents added that as these are seasonal foods, they are often in short supply, which explains their low consumption frequency, exemplified by vanilla, locally grown avocados, and *Persea schiedeana*.

On the other hand, the villagers commented that some edible plants grown are no longer adapted and have low production compared to other years. They attributed this situation mainly to the lack of rainfall and the continued presence of strong winds and hurricanes. According to the villagers, these changes in the weather cause low production of corn, coffee, beans, tomatoes, and chili peppers.

Discussion

Our results show that a high number of edible species are still maintained at the regional level, comparable to other regional ethnobotanical studies that have inventoried between 80 and 153 species in the smallholdings of the Totonac families of the Sierra Norte de Puebla (Del Ángel Pérez and Mendoza, 2004; Martínez-Alfaro et al., 2007). This number of edible species is higher than in other regions of Mexico, where less than 100 edible plants have been recorded (Solís and Casas, 2023). Moreover, if we consider the mean number of edible species grown per household (13.8 ± 7.05), this richness is high compared to other studies in rural peasant regions. For example, a study in Ghanaian farm households reported that some households grew up to eight edible plants, with a mean of 3.2 species per household (Bellon et al., 2020). A study in Kenya reports that the mean edible plant richness per household was 9.9 ± 4.3 (Oduor et al., 2019). Meanwhile, a study conducted in Mayan communities in Guatemala reported that households cultivate a mean of 15 ± 8 edible plants per household (Luna-González and Sorensen, 2018), which is very similar to our findings. However, the presence of these plant species in the plots was very low; out of a total of 101 species, 54 species were present in less than five plots, and most of these were either unrecorded or presented a very low frequency in the diet surveys. Fifty-three percent of the edible plant species inventoried in the farmer's plots was not recorded in the diet surveys conducted in the same communities, reflecting the apparent scarcity of these species. Therefore, they do not constitute a regular part of the diet and are likely to be used only when staple foods are scarce or in times of crisis, as noted by Mapes and Basurto (2016). The food groups with the highest proportion of such species include *quelites*, local vegetables, tubers, and fruit trees, which is consistent with the findings of Rivera-Núñez et al. (2022). An alternative explanation for this discrepancy between the species recorded in the farmer's plots and those mentioned in the diet surveys is that many of these plants are not consumed because family members, especially children, do not like their taste; consequently, even if the plants are present in the plots, they may not form part of the household's diet, as documented by other authors (Benítez et al., 2020).

The inhabitants of the Totonacapan region consider that the enhancement and cultivation of edible plants that complement their staple diet will continue to decline, primarily because many tubers, roots and local vegetables are difficult to cook. Furthermore, their collection and preparation are very time-consuming. Nuani et al. (2022) noted that some tubers and roots, such as *Manihot esculenta* and *Dioscorea alata* L., were rarely consumed because of several factors: their low presence in farmer's plots, unattractive taste and a lack of time required to prepare traditional meals using these plants as ingredients. A low volume of plants harvested and their complementary role in meals may also be a factor in the absence of many plant species in the dietary surveys. Some studies report that households do not mention food that only accompany meals, such as spices and some leafy greens (Duguma, 2020).

Among the 48species recorded in the plots and diet surveys, maize, one species of bean, one species of chili, squash, and local *chayotes*, all cataloged as traditional ingredients in the Mesoamerican peasant diet (Zizumbo-Villarreal et al., 2012), were common in the plots and presented the highest consumption frequency. Apart from *Citrus × sinensis* and *Musa* spp., whose fruits are mainly sold and not used for self-consumption, the remaining edible plants demonstrated a low consumption frequency and corresponded to those species that were least recorded in the plots. Edible plants such as tomatoes and other varieties of chilies and beans, considered staples in the peasant diet, showed a high consumption frequency in contrast to their low presence in the farm plots, which could be related to the fact that local and regional markets are selling foods from outside the region that are replacing those grown on the plots (Espinoza-Pérez et al., 2023). It is not clear whether the decrease in local production is because products can be bought in the markets or whether families buy in the market due to the decrease in local production. However, the dependence on the market for food varied between households, and even though we are referring to the same cultural and environmental area, species richness and consumption of edible plants differed considerably between families in the region. The families that consumed more self-produced and locally or regionally produced food maintained a greater richness of edible plants in their plots (groups A and D) compared to the families that depended predominantly on the market for food (groups B and C). Although several families in Group A owned plots rich in edible plant species, they consumed a low proportion of edible plant species. These results suggest that the more families depend on self-consumption to subsist, the greater the diversity of edible species in their farm plots; this finding supports the argument that crop diversification in farmers' agroecosystems increases the capacity for self-consumption in the diets of rural families (Bellon et al., 2020). Apart from staple crops such as maize and beans, there is another group of edible plants used in peasant diets that is not consumed by some families, even though they are present in their plots, we refer to *quelites*, fruit trees, and some local vegetables. This finding confirms that a large number of edible species in the plots of peasant farmers does not automatically imply that they are consumed frequently (Soto-Pinto et al., 2022).

This study reveals that, in some households, using available agricultural diversity can complement and diversify diets. This coincides with other studies that argue a positive association between edible plant richness and the nutritional quality of peasant household diets (Lachat et al., 2018; Benítez et al., 2020). However, there were families whose plots presented high species richness but exhibited the same consumption pattern as families from group A that consumed more food purchased from the market.

These results show that the contribution of agricultural diversity to farmer's diets appears to have diverse effects. As shown by other studies that have analyzed the relationship between crop and diet diversification, our results are mixed and depend on the context of the populations studied (Powell et al., 2015; Sibhatu and Qaim, 2018). Sibhatu et al. (2015) reported positive and significant associations between production and dietary diversity in Indonesia and Malawi, but not in Ethiopia and Kenya. To these findings, we would add that the household use of edible plants may differentiate within the same cultural and ecological region.

Study limitations

The discrepancy between the richness of plants in the plots and those consumed could be because the surveys only recorded food eaten at home, and many edible plants were consumed outside the household or not as part of regular meals, such as in the case of fruits that are often consumed in the plots where the fruit trees grow. A further consideration, particularly in the case of fruit, is that food availability is seasonal. Thus, some edible plants may not have been recorded as the surveys were conducted during nine months of the year. Another factor that may have contributed to the under-recording of plants in the diet surveys is that these were carried out in 2020, and edible species in plots were recorded in 2022.

Conclusion

Our study reveals that many plants found in the plots are marginal in the peasant farmer's diet, largely because of their low presence in the plots. This is reflected in the fact that more than half of the species inventoried in the plots were not mentioned in the diet surveys. The main reasons for the limited consumption of edible plants are that many people, especially children, no longer like their taste, they are difficult to cook, and that collection and preparation are time-consuming. Notwithstanding, farmers continue to tolerate and enhance these plant species in their plots, possibly as they are useful during food shortages or crises, given that ethnobotanical information showed that 83% of these species are used for self-consumption and occasionally for sale.

Although regional agricultural diversity is high, with 101 edible plants recorded, not all farm plots and family diets presented a substantial diversity of edible plants, and their relative use demonstrated a differential pattern among households. The families that relied more on self-consumption for subsistence maintained a greater richness of edible plants in their plots. For other families, a high richness of edible plants in their plots did not signify a diversified diet, while a large proportion of households maintained plots with few species of edible plants as their diet consisted predominantly of food purchased from the market.

The results of this research provide evidence of several factors that limit and contribute to the use of edible plants in peasant farming regions, such as the low presence of edible plants in plots, the importance placed by farmers on self-consumption, as well as preferences and tastes for local food. These are aspects that should be considered by researchers, farmers, nutritionists, and public policymakers in order to promote plants that are considered ignored and underutilized but have the potential to improve the nutrition of rural populations at the local, regional, and global levels.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by Studies with human participants were reviewed and approved by the Ethics Committee of El Colegio de la Frontera Sur. Consent was obtained from the local authorities of the study communities and parents where the study was conducted. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

JE-P: Conceptualization, Writing – original draft. SC-V: Conceptualization, Supervision, Validation, Writing – review & editing. HP: Formal analysis, Methodology, Supervision, Writing – review & editing. OM-F: Methodology, Supervision, Validation, Writing – review & editing. LS-P: Formal analysis, Supervision, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Aragaw, H. S., Nohr, D., and Callo-Concha, D. (2021). Nutritional potential of underutilized edible plant species in coffee agroforestry systems of Yayu, southwestern Ethiopia. *Agrofor. Syst.* 95, 1047–1059. doi: 10.1007/s10457-021-00626-6

Basurto-Peña, F. (2011). "Los quelites de México: especies de uso actual" in *Especies vegetales poco valoradas: una alternativa para la seguridad alimentaria*. eds. D. Castro-Lara, L. M. Mera-Ovando and R. Bye (México, D.F.: UNAM-SNICS-SINAREFI), 213.

Basurto-Peña, F., Castro, D., and Martínez-Alfaro, M. A. (2003). Edible begonias from the north of Puebla Mexico. *Econ. Bot.* 57, 48–53. doi: 10.1663/0013-0001

Basurto-Peña, F., Martínez-Alfaro, M. A., and Villalobos-Contreras, G. (1998). The Quelites (edible greens) in the sierra Norte de Puebla, Mexico: inventory and methods of preparation. *Bot. Sci.* 62, 49–62. doi: 10.17129/botsci.1550

Bellon, M. R., Hundie, K. B., Azzarri, C., and Caracciolo, F. (2020). To diversify or not to diversify, that is the question. Pursuing agricultural development for smallholder farmers in marginal areas of Ghana. *World Dev.* 125:104682. doi: 10.1016/j.worlddev.2019.104682

Benítez, K. M., Soto-Pinto, L., Estrada-Lugo, E., and Pat-Fernández, L. (2020). Huertos familiares y alimentación de grupos domésticos cafetaleros en la Sierra Madre de Chiapas. *Revista Agricultura, Sociedad y Desarrollo.* 17, 27–56. doi: 10.22231/asyd.v17i1.1321

Bruman, H. (1948). The culture history of Mexican vanilla. *Hisp. Am. Hist. Rev.* 28, 360–376. doi: 10.1215/00182168-28.3.360

Bye, R., and Linares, E. (2000). Los quelites, plantas comestibles de México. *Una reflexión sobre intercambio cultural. Biodiversitas.* 31, 11–14.

Del Ángel Pérez, A. L., and Mendoza, M. A. (2004). Totonac homegardens and natural resources in Veracruz Mexico. *Agric. Hum. Val.* 21, 329–346. doi: 10.1007/s10460-004-1219-9

Duguma, H. T. (2020). Wild edible plant nutritional contribution and consumer perception in Ethiopia. *Int. J. Food Sci.* 2020, 1–16. doi: 10.1155/2020/2958623

Espinoza-Pérez, J., Cortina-Villar, S., Perales, H., Soto-Pinto, L., and Méndez-Flores, O. G. (2023). Autoabasto en la dieta campesina del Totonacapan poblano (México): implicaciones para la agrodiversidad. *Región y Sociedad.* 35:e1717. doi: 10.22198/rys2023/35/1717

Frison, E. A., Smith, I. F., Johns, T., Cherfas, J., and Eyzaguirre, P. B. (2006). Agricultural biodiversity, nutrition, and health: making a difference to hunger and nutrition in the developing world. *Food Nutr. Bull.* 27, 167–179. doi: 10.1177/156482650602700208

García-Vazquez, R., López-Santiago, M. A., Valdivia-Alcalá, R., and Sánchez-Toledano, B. I. (2022). Use of traditional food and proposal for the dish of good eating for the Totonac region: totonaco plate of good eating. *AgroProductividad.* 1. doi: 10.32854/agrop.v15i1.2057

González-Bonilla, L. A. (1942). "Los Totonacas". Instituto de Investigaciones de la UNAM. *Repositorio Universitario Digital.* 4, 81–101.

Grivetti, L. E., and Ogle, B. M. (2000). Value of traditional foods in meeting macro- and Micro-nutrient needs: the wild plant connection. *Nutr. Res. Rev.* 13, 31–46. doi: 10.1079/095442200108728990

Hassen, A. (2021). Diversity and potential contribution of wild edible plants to sustainable food security in north Wollo, Ethiopia. *Biodiversitas* 22, 2501–2510. doi: 10.13057/biodiv/d220660

INALI (Instituto Nacional de Lenguas Indígenas). (2010). CatÁlogo de las Lenguas Indígenas Nacionales: Variantes Lingüísticas de México con sus autodenominaciones y referencias geoestadísticas. Available at: https://site.inali.gob.mx/pdf/catalogo_lenguas_indigenas.pdf

Kelly, I., and Palerm, A. (1952). *The Tajín Totonac, part I*. Washington: Smithsonian Institution. 359.

Kennedy, G., Ballard, T., and Dop, M. (2013). *Guía para medir la diversidad alimentaria a nivel individual y del hogar*. Roma: Organización de las Naciones Unidas.

Knez, M., Ranic, M., Gurinovic, M., Glibetic, M., Savic, J., Mattas, K., et al. (2023). Causes and conditions for reduced cultivation and consumption of underutilized crops: is there a solution? *Sustain. For.* 15:3076. doi: 10.3390/su15043076

Koukou, E., Amoussa-Hounkpatin, W., Sognigbé, N., Sounouke, C. V. D. P., Ntandou-Bouzitou, G., and Termote, C. (2022). Local knowledge of agricultural biodiversity and food uses of edible plant species in two agroecological zones of southern Benin. *Ethnobot. Res. Appl.* 23, 1–22.

Kuhnlein, H. V., and Receveur, O. (1996). Dietary change and traditional food systems of indigenous peoples. *Annu. Rev. Nutr.* 16, 417–442. doi: 10.1146/annurev.nu.16.070196.002221

Lachat, C., Raneri, J. E., Smith, K. W., Kolsteren, P., Van Damme, P., Verzelen, K., et al. (2018). Dietary species richness as a measure of food biodiversity and nutritional quality of diets, in *Proceedings of the national academy of sciences*. 115, 127–132. doi: 10.1073/pnas.1709194115

Luna-González, D. V., and Sorensen, M. (2018). Higher agrobiodiversity is associated with improved dietary diversity, but not child anthropometric status, of Mayan Achí people of Guatemala. *Public Health Nutr.* 21, 2128–2141. doi: 10.1017/S1368980018000617

Mapes, C., and Basurto, F. (2016). "Biodiversity and edible plants of Mexico in Mexican Ethnobotaby" in *Interactions of People and Plants in Mesoamerica*. eds. R. Lira, A. Casas and J. Blancas. 83–132. Available at: https://link.springer.com/chapter/10.1007/978-1-4614-6669-7_5

Martínez-Alfaro, M. A., Evangelista, V., Basurto, F., Mendoza, M., and Cruz-Rivas, A. (2007). Flora útil de la Sierra Norte de Puebla, México. *Revista Mexicana de Biodiversidad.* 78, 15–40. doi: 10.22201/ib.20078706e.2007.001.457

Martínez-Alfaro, M.A., Evangelista, V., Mendoza, M., Morales, G., Toledo, G., and Wong, A. (1995). *Catálogo de plantas útiles de la Sierra Norte de Puebla México Cuadernos del Instituto de Biología*, México. Universidad Nacional Autónoma de México.

Mehraban, N., and Ickowitz, A. (2021). Dietary diversity of rural Indonesian households declines over time with agricultural production diversity even as incomes rise. *Glob. Food Sec.* 28:100502. doi: 10.1016/j.gfs.2021.100502

Miller, V., Yusuf, S., Chow, C. K., Dehghan, M., Corsi, D. J., Lock, K., et al. (2016). Availability, affordability, and consumption of fruits and vegetables in 18 countries across income levels: findings from the prospective urban rural epidemiology (PURE) study. *Lancet Glob. Health* 4, e695–e703. doi: 10.1016/S2214-109X(16)30186-3

Neupane, N. P., Yadav, E., and Verma, A. (2022). "Cultural, practical, and socio-economic importance of edible medicinal plants native to Central India" in *Edible plants in health and diseases*. eds. M. H. Masoodi and M. U. Rehman (Singapore: Springer)

Nuani, F. O., Gido, E. O., Ayuya, O. I., and Musyoka, M. P. (2022). Demand analysis for selected roots and tubers among urban households of Nakuru County Kenya. *Cog. Food Agric.* 8:1. doi: 10.1080/23311932.2022.2093047

Oduor, F. O., Boedecker, J., Kennedy, G., and Termote, C. (2019). Exploring agrobiodiversity for nutrition: household on-farm agrobiodiversity is associated with improved quality of diet of young children in Vihiga Kenya. *PLoS ONE.* 14:e0219680. doi: 10.1371/journal

Phillips, O., and Gentry, A. H. (1993). The useful plants of Tambopata, Perú: I. Statistical hypotheses test with a new quantitative technique. *Econ. Bot.* 47, 15–32. doi: 10.1007/BF02862203

Powell, B., Thilsted, S. H., Ickowitz, A., Termote, C., Sunderland, T., and Herforth, A. (2015). Improving diets with wild and cultivated biodiversity from across the landscape. *Food Secur.* 7, 535–554. doi: 10.1007/s12571-015-0466-5

Rivera-Núñez, T., García-Barrios, L., Benítez, M., Rosell, J. A., García-Herrera, R., and Estrada-Lugo, E. (2022). Unravelling the paradoxical seasonal food scarcity in a peasant microregion of Mexico. *Sustain. For.* 14:6751. doi: 10.3390/su14116751

Sibhatu, K. T., and Qaim, M. (2018). Review: Meta-analysis of the association between production diversity, diets, and nutrition in smallholder farm households. *Food Policy* 77, 1–18. doi: 10.1016/j.foodpol.2018.04.013

Sibhatu, K. T., Krishna, V. V., and Qaim, M. (2015). Production diversity and dietary diversity in smallholder farm households. *Proc. Natl. Acad. Sci. U. S. A.* 112, 10657–10662. doi: 10.1073/pnas.1510982112

Solís, L., and Casas, A. (2023). "Cuicatec ethnobotany: plants and subsistence in San Lorenzo pa´ Palo, Oaxaca" in *Ethnobotany of the mountain regions of Mexico, ethnobotany of mountain regions*. eds. A. Casas and J. Blancas. 517–553.

Soto-Pinto, L., Escobar, C. S., Benítez, K. M., López, C. A., Estrada, L. E., Herrera, H. B., et al. (2022). Contributions of agroforestry systems to food provisioning of peasant households: conflicts and synergies in Chiapas Mexico. *Front. Sustain. Food Syst.* 5:756611. doi: 10.3389/fsufs.2021.756611

Zizumbo-Villarreal, D., Flores-Silva, A., and Colunga-García, P. M. (2012). The archaic diet in Mesoamerica: incentive for milpa development and species domestication. *Econ. Bot.* 66, 328–343. doi: 10.1007/s12231-012-9212-5

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Institutional arrangements in the promotion of sustainable livestock: an approach from the case of beef and dairy cattle production chains in Jalisco, Chiapas, and Campeche

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This study focuses on a policy and practice review of existing institutional arrangements within the beef and dairy cattle production sectors in the Mexican states of Jalisco, Chiapas, and Campeche. Acknowledging the critical role of robust governance frameworks in transitioning towards sustainable livestock agriculture, a collaborative governance approach is employed to holistically address environmental and production challenges. This approach underscores the importance of active participation, stakeholder collaboration, and contextual adaptation in decision-making processes. Classified as explanatory research, the study is grounded in a qualitative approach, covering a synchronous period from 2017 to 2022. Secondary sources such as public policies, international climate commitment reports, sector-specific reports, and databases were utilized to provide context and data regarding the analyzed institutional arrangements. Additionally, semi-structured information-gathering protocols were developed and, in conjunction with participant observation, administered to approximately 30 key stakeholders from public, private, academic, research centers, international cooperation, and civil society sectors involved in institutional arrangements in the aforementioned states. The findings highlight the significance of collaborative governance as a valuable alternative for addressing governance challenges in the livestock sector, particularly when hierarchical or market-oriented approaches are less effective. The diversity of identified institutional arrangements, ranging from hierarchical to polyarchic, emphasizes the need to acknowledge the specificities of the context in which they operate and adapt strategies accordingly. This analysis contributes to the growing discussion on sustainable livestock farming and the fundamental role of institutional arrangements in promoting responsible practices and mitigating environmental impacts. As demands for natural resources and environmental awareness increase, understanding and strengthening these arrangements become essential to balance livestock production and environmental conservation.

KEYWORDS
livestock sustainability, institutional arrangements, collaborative governance, public policies, stakeholder engagement

1 Introduction and problem statement

1.1 General context

Livestock farming plays a crucial role in the global economy and food security. It is a significant source of protein and essential nutrients worldwide, and a key economic activity for millions of people. In Mexico, livestock farming is not only a critical economic activity but also an integral part of culture and rural life. As reported by the Government of Mexico (2023b), livestock contributes substantially to the nation's GDP (Gross Domestic Product), particularly in the primary sector (39,7%). Mexico stands as a major global player in the production of animal-origin meat protein and bovine milk, ranking seventh and fifteenth worldwide, respectively (Government of Mexico, 2023a).

At the national level, beef cattle farming is the primary source of animal protein, accounting for 82.1% of animal-origin food (IICA, 2021). This sector occupies 56% of Mexico's land area, equivalent to 1.1 million square kilometers (IICA, 2021; Vásquez Aguilar, 2023), highlighting its extensive economic and environmental footprint. However, the expansion of livestock farming has led to ecological challenges, including habitat degradation and fragmentation, particularly in 24 states of the country since 2002 (Vásquez Aguilar, 2023).

Conventional livestock farming practices have been associated with various negative impacts, such as deforestation, biodiversity depletion, water pollution, and significant greenhouse gas emissions (GHG). Notably, these GHG emissions account for 68% of the total emissions within the agricultural sector (IICA, 2021) In response to these challenges, sustainable livestock farming has emerged as a pivotal approach. This approach aims to reconcile livestock production with environmental conservation, animal and human health, local economic dynamism, and social well-being. It focuses on improving productive efficiency, minimizing negative environmental impacts, promoting animal welfare, ensuring equity in production chains, and fostering local stakeholder participation in decision-making processes.

The transition towards sustainable livestock farming necessitates solid institutional arrangements that actively support these changes. Defined as "patterns of relationships among multiple institutions in a specific context" (Ostrom, 2014) these arrangements are crucial in defining incentives, responsibilities, and interactions not only among various stakeholders within the production chains but also between producers, consumers, the private sector, governmental and non-governmental organizations, and research institutions. As tangible outcomes of governance frameworks, institutional arrangements play a pivotal role in influencing relational dynamics, resource allocation, and conflict resolution, thereby facilitating the shift towards more sustainable practices in livestock farming.

1.2 Works related

Over the past decade, there has been a marked increase in research into the role of governance in the agricultural sector. These studies stem from global efforts to understand and improve resource management and policy-making for sustainable agricultural development. They have evolved from centralized state management models to more participative and decentralized methods involving a wide range of actors, including the private sector, civil society, and local communities.

A key precursor to this research is found in environmental governance studies, particularly in forestry and water domains, which have a rich historical record. Internationally, the contributions of Elinor Ostrom's groundbreaking work in the governance of common-pool resources, such as forests and water, has received international recognition (Ostrom, 1990, 2010a; Poteete et al., 2010). Arlin Vatn, known for his contributions in institutional economics and environmental governance, is also noteworthy (Vatn, 2005, 2020; Aasen and Vatn, 2021). Brendan Coolsaet's focus on environmental justice and biodiversity governance has been influential (Alvarez and Coolsaet, 2020; Coolsaet et al., 2020), along with Thomas Sikor's expertise in land governance and forest resources (Sikor, 2008, 2013), and Anne Larson's significant research on forest governance and indigenous rights (Larson and Petkova, 2011; Petkova et al., 2011).

In Latin America, Eduardo Brondizio is distinguished for integrating anthropology with environmental sustainability (Tengo et al., 2014; Brondizio and Le Tourneau, 2016; Chazdon et al., 2021). The works of Cristiana Simão and Déborah Santos in natural resource management and environmental governance (Santos et al., 2021, 2022) and María Tengö's focus on socio-ecological system governance emphasizing indigenous and local knowledge (Enqvist et al., 2020; Tengö et al., 2022) are equally important.

Agricultural governance, on the other hand, has become a relevant field of study in response to the region's particular challenges: inequality in land tenure, the critical role of agriculture in local economies, and the urgency of conserving biodiversity amidst agricultural expansion. Research has grown concerning how institutional frameworks and policies can support economically efficient, socially equitable, and environmentally responsible agricultural practices. From an agroecological perspective (Altieri et al., 2020; Altieri and Nicholls, 2020), focusing on data use to support the decision-making process (Li et al., 2023) and based on knowledge management (FONTAGRO, 2019), these contributions have been pivotal, mainly centered on the need for collaborative work, access to information, and co-design and co-participation in decision-making processes.

Overall, research has increased in recent years around how institutional frameworks and policies can support agricultural practices that are economically efficient, socially fair, and environmentally responsible. This aligns with the fact that governance in the Latin American agricultural sector has become more complex, recognizing the need for multidisciplinary and multi-level approaches that address interactions between policies at local, national, and international levels.

There are also significant contributions to the field, such as efforts to document the political-institutional conditions that recreate certain governance schemes for the cases of the three Mexican states analyzed in this article (Avalos, 2023a,b,c) as well as for Costa Rica (Avalos and Chacon, 2023; Avalos, 2023a).

Despite the significant advances demonstrated by such studies, having a typology that allows mapping institutional arrangements within the framework of productive chains to dissect the governance scheme as a whole has been a pending task. Theoretical contributions by Elinor Ostrom (Ostrom, 1990, 2010a,b; Poteete et al., 2010) and Ansell and Gash (2007) have allowed this study to go further, offering a typology of institutional arrangements that encompass a particular governance scheme, as woven around the productive chains of meat and milk in the states of Chiapas, Jalisco, and Campeche.

1.3 Paving the path for sustainability: the contributions of this study

This article, set within the backdrop of the *"Promoting Biodiversity Conservation through Climate-Smart Agro-silvopastoral Practices in Livestock-Dominated Landscapes"* project,[1] embarks on a critical examination of institutional arrangements pivotal for sustainable livestock farming. The contributions are manifold:

- Unveiling institutional dynamics: this study uncovers various institutional arrangements, from hierarchical to polyarchic, each adapted to local contexts. This provides a governance blueprint that respects regional differences.
- Promoting collaborative governance: it underscores the essence of collaborative governance. The diversity in institutional arrangements elucidates the need for strategies acknowledging local context nuances, thus enhancing decision-making quality, transparency, and accountability.
- Guiding future research: this work paves the way for comparative analyses across different regions, deepening the understanding of how institutional frameworks evolve and adapt, and evaluating stakeholders' perceptions to glean insights into the operational challenges and opportunities.

1.4 Methodology

To elevate the methodological rigor of this study, a comprehensive and multi-dimensional approach is adopted, which integrates both qualitative and quantitative data for a thorough mapping of production chain structures. Emphasizing an explanatory stance, the research systematically explores the evolution of institutional arrangements within a governance framework. This blended methodology facilitates a nuanced analysis of developments, challenges, and future prospects in the livestock sector with enhanced precision, covering the period from 2017 to 2022.

Incorporating a neo-institutional perspective, this research method analyzes governance structures in depth. This approach is augmented by a sustainable value chain analysis, focusing on the economic, environmental, and social impacts within the livestock industry. Such a dual-method strategy ensures a comprehensive examination of institutional arrangements, capturing the intricate dynamics and complexities of sustainable agricultural practices.

Key components of this methodology include:

- A neo-institutionalist perspective that emphasizes collaboration and cooperation, as proposed by Ansell and Gash. This viewpoint considers the complexity of value chains, their interdependence with other economic sectors, and the inherent relational and power dynamics (Ansell and Gash, 2007).
- The sustainable value chain approach, which identifies critical stages, value flows, and stakeholder relationships, aims to deliver products or services to differentiated markets, ensuring equitable distribution of benefits.
- An exploration of institutional arrangements, defined as "patterns of relationships among multiple institutions within a specific context" (Ostrom, 2014). This includes norms, rules, organizational structures, and public policies that govern interactions and decision-making processes relevant to resource allocation and conflict resolution.

Through this integrated methodological framework, the study achieves a rigorous and holistic understanding of the factors influencing sustainable livestock farming.

Secondary sources such as public policies, international climate commitment reports, sector-specific reports, and data bases were utilized to provide context for the livestock sector and data regarding the analyzed institutional arrangements. Subsequently, semi-structured information-gathering protocols were developed, and in conjunction with participant observation, were administered to approximately 30 key stakeholders from the public, private, academic, research centers, international cooperation, and civil society sectors involved in institutional arrangements in the states of Jalisco, Chiapas, and Campeche.

For the purposes of this article, institutional arrangements have been analyzed using a typology that distinguishes between hierarchical, market-based, community-based, and polyarchic arrangements, built upon the contributions of Ansell and Gash (2007) and Ostrom (2014).

Regarding data analysis, a qualitative approach was employed, which relied on the analysis of interview results to identify emerging patterns and themes grounded in theory.

1.5 Structuring the narrative: organization of the article

The structure of this article is thoughtfully designed to guide readers through the intricacies of sustainable livestock farming within the complex fabric of institutional arrangements:

- Introduction and problem statement: the article opens by setting the scene on the challenges and objectives of sustainable livestock farming.
- Methodological approach: a qualitative lens is applied to dissect the workings of various institutional arrangements, providing a comprehensive view that informs the study's findings.
- Findings and discussions: the core of the article lies in its detailed analysis of these arrangements, their effectiveness, and their influence on sustainable practices within the livestock sector.
- Conclusions and recommendations: the narrative culminates with actionable insights and recommendations, charting a course for future initiatives and policy-making to foster sustainable livestock farming practices.

Each section builds upon the previous, ensuring a coherent and informative journey for the reader, ultimately leading to a set

1 BioPaSOS, an acronym for 'Biodiversity and Sustainable Agro-silvopastoral Landscapes', was an initiative active from 2017 to 2022. It aimed primarily at empowering livestock producers through the adoption of sustainable agro-silvopastoral practices. The project's core mission was to mitigate the adverse effects on biodiversity inherent in traditional livestock farming, encourage decisions grounded in robust scientific evidence, and foster a collaborative approach in the management of value chains (CATIE, 2023).

of well-founded conclusions and recommendations that promise to shape future discourse and action in the realm of sustainable livestock farming.

2 Sections on assessment of policy/guidelines options and implications

In this section, a detailed evaluation of the institutional arrangements related to the promotion of sustainable livestock farming in the states of Jalisco, Chiapas, and Campeche is provided. As outlined, these arrangements are categorized into hierarchical, market-based, community-based, and polyarchic types. This typology, informed by the contributions of Ansell and Gash (2007) and Ostrom (2014) offers a structured framework for the analysis, as visually represented in the accompanying diagram.

The subsequent section delves into the specifics of these arrangements, exploring each category in detail. An in-depth understanding of these types is essential for comprehending the broader context of sustainable livestock farming within the studied regions, highlighting how these arrangements influence practices and policies. The analysis methodically examines the implications of these arrangements, providing insights into their effectiveness and areas for potential improvement.

3 Hierarchical institutional arrangements

Within this study, three sub-types of hierarchical institutional arrangements have been identified:

3.1 Regulations and norms imposed by authorities

In all three analyzed states, the existence of federal and state government regulations and norms that establish requirements and procedures for livestock production is observed. In many cases, these regulations also emphasize environmental conservation within the context of production practices.

3.2 State-level supervisory and regulatory bodies

The oversight and regulation of livestock activity are carried out by key state institutions (see Figure 1). In each of the reference states, organizations with defined roles have been established to ensure compliance with regulations and norms related to livestock production.

Traditionally this role had been within the purview of the State Departments of Agriculture, over time, a closer alignment between production-focused supervision and environmental oversight has been observed. This has allowed for the identification of governmental entities linked to the Departments of Environment in this exercise. Additionally, state-level instances, at the federal level, are involved in this role of supervision and regulation (see Figures 2–6).

3.3 State and/or federal support programs with hierarchical conditions

Finally, concerning state or federal support programs with hierarchical conditions, various initiatives have been identified as the first element demonstrating the presence of institutional arrangements of this type (see Table 1).

As a second element, in all states, the role of "Operating Rules" can be observed, which constitute a set of guidelines and directives established by government agencies, both at the federal and state levels, to regulate and guide the implementation of public programs and policies in different areas. These rules define the procedures, requirements, eligibility criteria, and operational methods of government programs and projects.

Operating rules constitute requirements for the use of certain programs; therefore, they can be considered hierarchical in nature, as they are designed with the purpose of ensuring the proper execution of public resources, transparency in their use, and the efficient delivery of benefits to citizens or target groups who are recipients of these programs. These rules provide a legal and operational framework that must be followed to request, access, and utilize resources and support provided by the government in various areas, such as agriculture, livestock, and the environment.

These programs exemplify how state and federal authorities have established requirements and conditions for providing support to livestock producers, with the aim of promoting more responsible and sustainable practices.

Finally, it is possible to identify that, for the State of Jalisco, there are programs focused on the provision and regulation of ecosystem services, which are operated with state funds. These programs aim to compensate agricultural producers for practices that generate environmental benefits, such as the conservation of natural areas, the protection of water sources, or the reduction of greenhouse gas emissions. These state-implemented programs incentivize agricultural producers to adopt sustainable livestock practices. In this regard, the programs available in the state are as follows: Sustainable Forest Development Program of the State of Jalisco 2023 (Component IV). Component I: Sustainable Forest Management (SFM). Component II: Compensation for Environmental Services (CES). Component III: Afforestation for Silvo pastoral Systems (ASS). Component IV: Forest Carbon Projects (FCP). Component V: Forest Protection with Health Actions (FPH).

For the State of Chiapas, no programs supporting livestock producers with state funds for the provision and regulation of ecosystem services have been identified. However, on some occasions, the State Government has developed subsidy programs for the acquisition of breeding stock.

In Campeche, six support programs have been identified to benefit livestock producers, including the following: the Electric Fence Implementation Program, aimed at intensifying pasture management for better utilization of grazing resources for livestock feed; the Implementation of Preventive Actions Program in Livestock Production Units against the Effects of Drought, with its main objective being to support producers with animal supplementation during critical times of the year; the Equipment Implementation Program for Increased Dairy Production, which seeks to support producers with technologically advanced milking

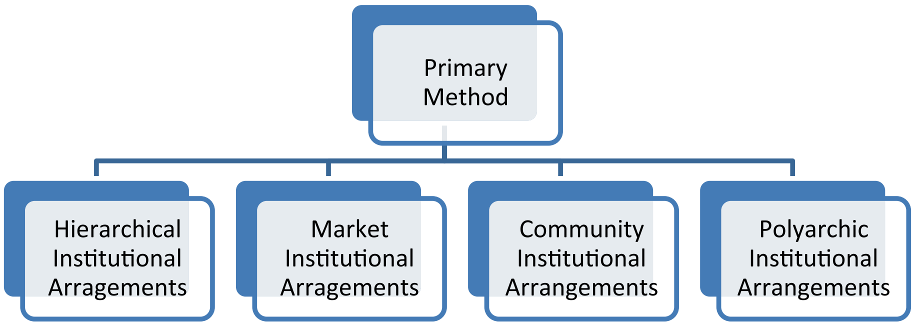

FIGURE 1
Structural diagram of the primary method and its subsections.

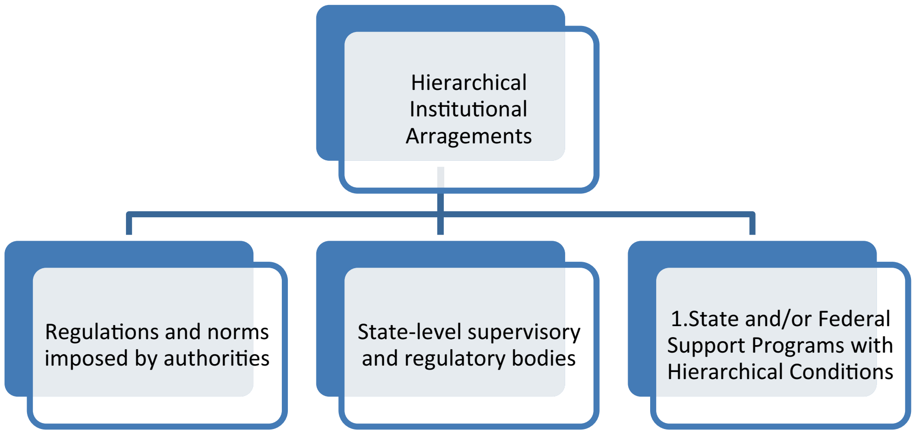

FIGURE 2
Subtypes of hierarchical institutional arrangements.

equipment; the Bovine Herd Productivity Increase Program, aimed at improving and increasing livestock herds through artificial insemination techniques; and the Breeding Stock Acquisition Subsidy Program. Additionally, there is an Extension Program for Agricultural Development.

4 Institutional market arrangements

To provide a structured understanding of the market dynamics within Jalisco, Chiapas, and Campeche, our analysis delineated five distinct subtypes of institutional market arrangements. This classification emerged from a systematic examination of the data, guided by our research objectives, and informed by the theoretical framework established in our methods section.

4.1 Differentiation strategies

In our results, differentiation has been meticulously analyzed, considering multiple facets such as pricing strategies, the impact of certifications, the role of quality seals, and the effectiveness of various marketing channels. This comprehensive analysis allows for a nuanced understanding of market dynamics and their influence on sustainable livestock farming.

In Chiapas, there is a clear interest on the part of entities such as SAGyP and SEMAHN (Secretaría de Medio Ambiente e Historia Natural), as well as non-governmental institutions, to promote the differentiation of prices for sustainable livestock products. Furthermore, efforts are underway to develop seals that allow for the differentiation of livestock products that meet environmental standards, incentivizing producers to adopt sustainable practices. Despite these advances, there is still a pending task to work on specific strategies, such as labeling and traceability that would enable consumers to know the origin and production practices of livestock products. This would facilitate the selection of products coming from sustainable production systems, promoting the demand for sustainability-focused livestock.

In Jalisco, the differentiation process has been initiated through the "Deforestation-Free Pasture-Based Beef Initiative," promoted by the Northeast and West Fund Civil Association (FONNOR A.C.), currently undergoing the implementation phase and is anticipated to commence operations before the conclusion of 2023. This innovative production and marketing model aims to promote sustainable livestock through price differentiation, the presence of a seal, proper label management, and ensuring product traceability.

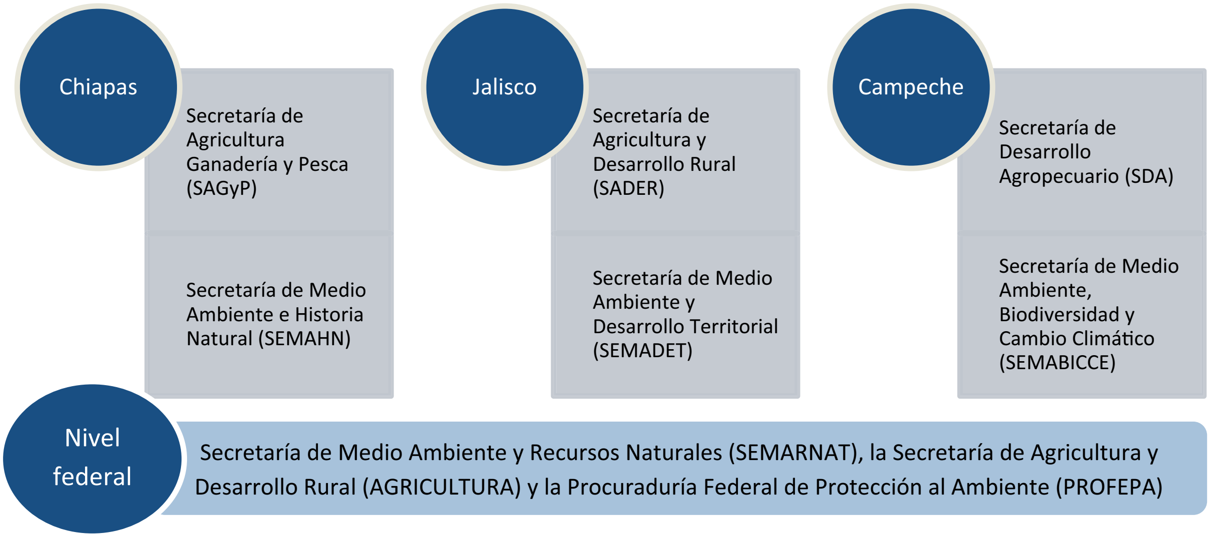

FIGURE 3
State-level supervisory and regulatory organizations in each state.

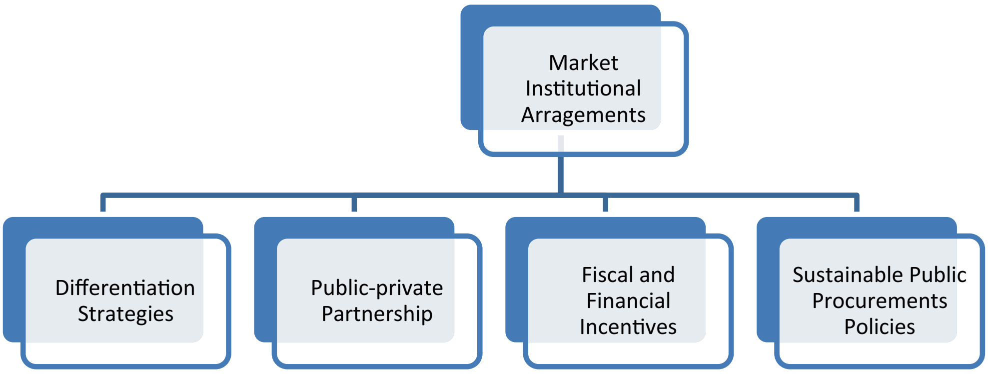

FIGURE 4
Subtypes of market institutional arrangements.

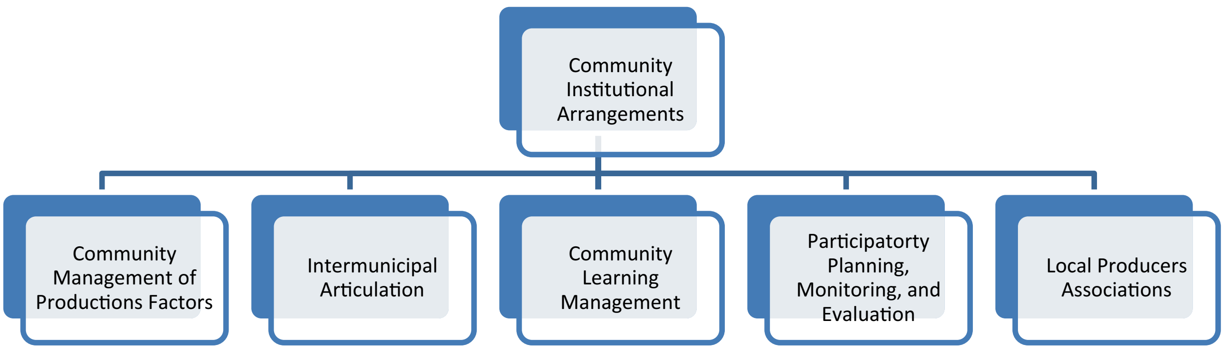

FIGURE 5
Subtypes of community institutional arrangements.

Finally, in Campeche, it has not been possible to identify specific institutional market arrangements focused on product differentiation from the aspects described above.

4.2 Public-private partnerships

It can promote sustainable livestock through joint agreements and programs. These partnerships may involve governments, businesses, producer organizations, and other relevant stakeholders, enabling the implementation of strategies that promote sustainable practices in the livestock value chain. Such partnerships have naturally evolved in the three states through multi-stakeholder coordination spaces, public-private initiatives, or research efforts with academia aimed at combining efforts and synergies to address common sectoral challenges and transition toward sustainable schemes.

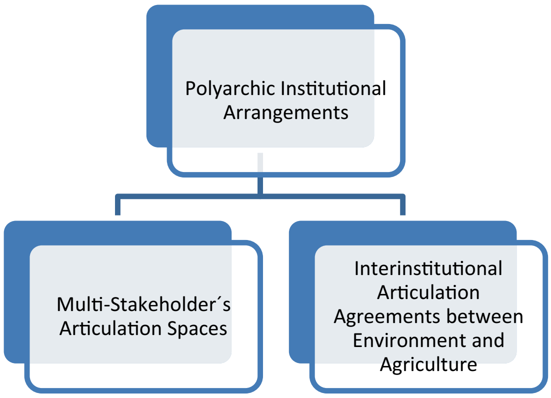

FIGURE 6
Subtypes of polyarchic institutional arrangements.

4.3 Fiscal and financial incentives

To promote the adoption of sustainable practices in livestock. These institutional arrangements may include tax exemptions for livestock products from sustainable systems, preferential loans, or subsidies for investments in more sustainable infrastructure and technologies. In the case under examination, it was only possible to identify the Sustainable Projects Support Program (ProSostenible) granted by the Trusts Established in Relation to Agriculture (FIRA). This program aims to facilitate access to credit for investment projects in the agricultural sector that generate environmental benefits and/or improve the capacity for climate change mitigation and adaptation. This program is present throughout the country, with small and medium-sized producers as its primary target population.

4.4 Sustainable public procurement policies

It establishes sustainability criteria in the acquisition of livestock products by government entities, promoting the demand for livestock products from sustainable systems. They can have a significant impact as major buyers in the market. Like the previous case, it has not been possible to identify institutional arrangements in this area in the three states under study.

This highlights the accomplishments of the states concerning these institutional arrangements. However, it is not solely the hierarchical role of the state and market relationships that shape these institutional setups.

TABLE 1 State and/or federal support programs with hierarchical conditions.

State	Program	Objective
Chiapas	Subsidy program for the acquisition of breeding stock	Providing support to livestock producers through the provision of breeding stock for genetic enhancement in livestock herd productivity.
Campeche	Electric fence implementation program:	Enhancing pasture management to achieve improved utilization of grazing resources for livestock feed.
	Preventive actions program in livestock production units against the effects of drought	Supporting producers with animal supplementation (molasses, silage, and hay) during periods of drought
	Implementation of equipment program for increased dairy production:	Support for milking equipment and training for small and medium-sized producers.
	Program for increasing bovine herd productivity	Supporting small and medium-sized producers through artificial insemination schemes."
	Breeding stock acquisition subsidy program	Providing support to livestock producers through the provision of breeding stock to enhance genetic improvement in the productivity of the cattle herd.
	Extension program for agricultural development	Supporting producers with technical assistance and training.
Jalisco	Field action program for climate change	Designed to address climate challenges in livestock farming.
	Young heirs of the field support program	Targeted at young individuals involved in livestock farming and inheritors of rural traditions.
	Program for the Promotion of agricultural production and modernization	It aims to enhance productivity and modernization in the livestock sector.
	Program for genetic improvement of cattle, sheep, and goats	Focused on the genetic enhancement of livestock to increase quality and yield.
	Sustainable forestry development of the state of Jalisco (FIPRODEFO):	Aimed at the sustainable development of forest resources.

The following offers a reflection on what is referred to as 'community arrangements,' further enhancing the perspective of this typology.

5 Community institutional arrangements

Community institutional arrangements encompass an approach where the local community plays a vital role in decision-making and the management of natural resources and collective interests. These arrangements are based on active participation by community members who collaborate in creating norms and governance mechanisms that regulate the use and conservation of resources.

Within these arrangements, the community shares the responsibility for collectively managing resources, seeking mutual benefits. Decision-making processes are inclusive and participatory, granting a voice and vote to all members in relevant matters. This collaboration fosters cooperation and mutual trust, contributing to the effectiveness and sustainability of the agreements reached.

There are countless examples of community institutional arrangements that vary depending on culture, context, and the specific needs of each community. However, they all share the characteristic of promoting collaboration and empowering community members in decision-making and the management of shared resources. During the analysis conducted in Jalisco, Chiapas, and Campeche, five subtypes of these arrangements were identified:

5.1 Community management of production factors

This encompasses the administration of communal lands and ecosystem services. For example, in Jalisco, community land management is seen in indigenous areas, as well as the management of ecosystem services by *ejidos*[2] in the three states studied. In Chiapas, there are initiatives for the joint management of natural resources.

5.2 Intermunicipal articulation

This concept stands out for its innovation in territorial resource management in the state of Jalisco. In this state, 11 cross-municipal boards have consolidated experiences in intermunicipality,[3] illustrating how the intersection between environmental protection and sustainable livestock production is addressed at the community level.

5.3 Community learning management

Projects such as model ranches, experimental farms, and field schools (ECA) facilitate the transfer of knowledge and technologies toward more sustainable production practices. Through the BioPaSOS Project, these entities were established in the three states, influencing other communities. In Jalisco, intermunicipal boards and SADER have also promoted these spaces for community learning management, even extending technical assistance to other productive sectors.

5.4 Participatory planning, monitoring, and evaluation

In Jalisco, a participatory Regional Territorial Planning program has been implemented, addressing livestock-related issues. Additionally, within national protected areas and certain ejidos in Chiapas, participatory monitoring and evaluation processes are carried out.

5.5 Local producer associations

These associations are present in all three states, enabling collaboration among producers at the local level.

Community institutional arrangements focus on promoting the participation of local communities in decision-making processes and the management of shared resources. In Jalisco, Chiapas, and Campeche, various forms of community collaboration were identified, ranging from the management of production factors to participatory planning and producer associations. The significance of involving communities in the pursuit of sustainable solutions is reflected in these approaches. After concluding this section, we will delve into the study of polyarchic institutional arrangements.

6 Polyarchic institutional arrangements

Polyarchic institutional arrangements represent a governance approach that promotes participation and shared decision-making among diverse stakeholders, such as government, the private sector, civil society, academia, and local communities. These arrangements seek to strengthen collaboration and shared responsibility in problem-solving and resource management.

In polyarchic institutional arrangements, it is acknowledged that multiple stakeholders possess diverse interests and knowledge that can contribute more effectively to governance. The goal is to prevent the concentration of power in a single stakeholder or group, promoting inclusivity and equitable participation in decision-making.

These institutional arrangements are grounded in the premise that effective governance involves collaboration and cooperation among diverse stakeholders. The aim is to establish spaces for dialogue and

2 In Mexico, an "ejido" is a type of communal agricultural unit that was established as part of the agrarian reform in the early 20th century. Ejidos are communal lands distributed among the members of a community or village, and land ownership is not individual but belongs to the community as a whole. Ejidos were created with the aim of promoting land redistribution and agrarian justice, providing access to land for those who historically did not have it.

3 In Mexico, "intermunicipality" refers to the collaboration and cooperation among municipalities or local governments to address issues or matters of common interest that transcend the administrative boundaries of a single municipality. This entails multiple municipalities working together in the planning and execution of projects, programs, or policies that have a regional impact or require a broader coordination than what an individual municipality could provide.

negotiation where stakeholders can exchange information, share perspectives, and make joint decisions.

In the study conducted in Jalisco, Chiapas, and Campeche, two specific subtypes were identified within this group of institutional arrangements:

6.1 Multi-stakeholder's articulation spaces (collectives/dialogue platforms)

These spaces bring together diverse stakeholders for dialogue and collaboration on specific issues. An example is the Sustainable Livestock Group in Chiapas, the Silvo pastoral Operational Group in Jalisco, and the Working Group on Sustainable Livestock Agroecosystems (AGS.CAM). These spaces have also attempted to promote participatory research agendas among academics, researchers, and the public sector. However, sustainable long-term proposals have not yet been consolidated.

6.2 Interinstitutional articulation agreements between environment and agriculture

This approach refers to the strong relationship between the Environmental and Agricultural Secretariats. In Jalisco and Chiapas, this relationship unfolds smoothly. In Campeche, the relationship is more technical and focused on specific issues. This collaboration aims to coordinate efforts between different government entities to address challenges at the interface between agriculture and the environment.

This research highlights the role of collaborative governance in sustainable livestock farming. It emphasizes the need for context-specific strategies in diverse institutional arrangements. Concluding this section, we will explore a general discussion of these findings.

7 Discussion

The investigation of institutional arrangements across the beef and dairy production chains in Jalisco, Chiapas, and Campeche has unveiled the dynamic forces shaping sustainable livestock farming. The discussion herein is grounded in a rigorous assessment of these arrangements, ranging from hierarchical to polyarchic, and decisively underscores their role in resource management and environmental stewardship within the sector. A meticulous analysis of the collected data reveals clear links between the structure of these arrangements and their operational outcomes, casting light on the pathways to sustainable livestock management.

While hierarchical arrangements have streamlined sustainable practices and adherence to regulations, they have also surfaced challenges, notably in stakeholder inclusion and empowerment. Centralized decision-making may disenfranchise local stakeholders, potentially engendering resistance and undermining the legitimacy of initiatives. Addressing the nuances of stakeholder engagement is critical, with a focus on enhancing local input and enabling change from the grassroots level.

Concurrently, the challenge lies in fostering inter-institutional collaboration and transparent responsibility sharing, critical for the efficacious application of regulations and standards. The discourse contemplates the ramifications of these arrangements, probing into how they can be reformed to facilitate a more inclusive and sustainable trajectory for livestock farming.

Another challenge is ensuring proper coordination and collaboration among different institutions involved in supervising and regulating livestock production. It is essential for there to be open communication and a clear distribution of responsibilities to ensure the effective implementation of established regulations and standards.

Market-based arrangements are dissected for their potential in economic incentivization and the promotion of sustainable practices through product differentiation and partnerships. The efficacy of such strategies is critically analyzed, with recommendations for bolstering their implementation highlighted as essential for progress.

Community arrangements are celebrated for catalyzing local involvement and decision-making, underpinning the promotion of sustainable practices. This research accentuates how such collaborative frameworks not only bridge livestock production with environmental conservation but also empower communities to act in their collective interest.

Within the scope of this study, the progress achieved through community agreements is attributed to the ejidal system's unique approach to territorial management and local decision-making in Mexico, which inherently supports the devolution of certain decision-making aspects.

The discourse culminates with an examination of polyarchic arrangements, advocating for a governance model that is inclusive of diverse stakeholder perspectives, thereby enhancing the formulation and implementation of sustainable strategies. Despite the advantages, the necessity to solidify these arrangements and empower local decision-making is underscored to ensure adaptability to specific community contexts.

The discussion does not shy away from the inherent limitations within collaborative governance, such as the complexities of establishing binding agreements and the risk of excluding vital stakeholders. An imperative component of this dialogue is the strategizing of financial mechanisms to sustain these governance spaces, recognizing that without fiscal support, the feasibility of executing sustainable initiatives is significantly compromised.

8 Conclusions and recommendations

This study contributes novel insights into the governance of sustainable livestock farming by critically examining a range of institutional arrangements in Jalisco, Chiapas, and Campeche. Our dual-method approach, integrating both qualitative and quantitative analyses, offers a nuanced perspective not commonly found in the existing body of literature, which typically focuses on singular governance models. This methodological innovation allows for direct correlation between governance structures and sustainable outcomes in livestock management. Nonetheless, the study is candid about its limitations, including the variability of stakeholder engagement and resource constraints, which could impact the application of these arrangements.

Future research is encouraged to conduct comparative analyses across different regions, which will deepen the understanding of how institutional arrangements adapt to various contexts. There's also a call for investigations into stakeholder perceptions to unravel the intricacies of collaborative governance.

The actionable recommendations distilled from this study aim to propel sustainable livestock farming forward by:

- Enhancing local participation: encouraging the inclusion of local stakeholders in governance processes, potentially through advisory committees and capacity-building initiatives.
- Strengthening coordination: advocating for better cooperation among institutions overseeing livestock production to facilitate the enforcement of regulations and standards.
- Empowering communities: promoting community management practices that allow locals to make environmentally beneficial decisions, leveraging the success of intermunicipality models.
- Supporting collaborative governance: emphasizing the need for multi-stakeholder dialogue spaces and robust interinstitutional agreements for effective collaborative governance.
- Encouraging context-specific adaptation: recommending strategies be tailored to the distinct cultural, political, and socioeconomic contexts of each region for greater impact.

These recommendations are designed to address the identified challenges and capitalize on the opportunities to enhance the livestock sector's sustainability.

In summary, the research accentuates the value of collaborative governance in addressing sectoral challenges, highlighting the diversity of institutional arrangements that require context-sensitive strategies. The inclusive nature of collaborative governance, engaging a wide array of stakeholders, is essential for fostering trust, mutual learning, and commitment to sustainable policy implementation.

The study is pivotal in enhancing our comprehension of how institutional arrangements can drive sustainable livestock farming in Mexico, recognizing the complexities and the contingent nature of such arrangements.

By setting a clear direction for future research and offering a suite of evidence-based recommendations, the study seeks to influence policymakers and industry stakeholders to foster a livestock sector that is inclusive, sustainable, and responsive to the evolving environmental landscape.

Author contributions

IA: Conceptualization, Formal analysis, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing. CS: Funding acquisition, Project administration, Writing – review & editing. JB: Conceptualization, Investigation, Writing – review & editing. JJ-T: Conceptualization, Investigation, Writing – review & editing. EP-S: Conceptualization, Investigation, Writing – review & editing. AE: Conceptualization, Investigation, Methodology, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Aasen, M., and Vatn, A. (2021). Institutional context, political-value orientation and public attitudes towards climate policies: a qualitative follow-up study of an experiment. *Environ. Values* 30, 43–63. doi: 10.3197/096327120X15752810324075

Altieri, M., and Nicholls, C. (2020). Agroecology: challenges and opportunities for farming in the Anthropocene. Ciencia e Investigación Agraria: Revista Latinoamericana de Ciencias de La Agricultura, 47(3), 204–215. Available at: https://dialnet.unirioja.es/servlet/articulo?codigo=8049349

Altieri, M., Salazar, O., Rojas, C., Baginsky, C., Boza, S., Lankin, S., et al. (2020). Challenges for agroecology development for the building of sustainable Agri-food systems. *Int. J. Agri. Nat. Res.* 47, 152–158. doi: 10.7764/ijanr.v47i3.2308

Alvarez, L., and Coolsaet, B. (2020). Decolonizing environmental justice studies: a Latin American perspective. *Environ. Justice* 31, 50–69. doi: 10.1080/10455752.2018.1558272

Ansell, C., and Gash, A. (2007). Collaborative governance in theory and practice. *J. Public Adm. Res. Theory* 18, 543–571. Available at: https://academic.oup.com/jpart/article/18/4/543/1090370

Avalos, I. (2023a). *Construction of institutional arrangements in agricultural governance schemes resulting from climate commitments: the case of the coffee and livestock production chains in Costa Rica 2015–2022*. Salamanca: University of Salamanca.

Avalos, I. (2023b). El rol de la coordinación institucional entre las Secretarías de Agricultura y Ambiente para la promoción de una ganadería sustentable que contribuya a las ambiciones climáticas del estado de Chiapas, México. Available at: http://biblioteca.catie.ac.cr/cgi-bin/koha/opac-detail.pl?biblionumber=150869

Avalos, I. (2023c). Gobernanza colaborativa vinculada a la promoción de ganadería sostenible: El caso de Campeche, México. Available at: http://biblioteca.catie.ac.cr/cgi-bin/koha/opac-detail.pl?biblionumber=150870

Avalos, I., and Chacon, M. (2023). Gobernanza colaborativa en la toma de decisión vinculada a la promoción de ganadería sostenible El caso de Costa Rica. Available at: http://biblioteca.catie.ac.cr/cgi-bin/koha/opac-detail.pl?biblionumber=150900

Brondizio, E., and Le Tourneau, F.-M. (2016). Environmental governance for all. *Science* 352, 1272–1273. doi: 10.1126/science.aaf5122

CATIE. (2023). BioPaSOS Project. About. Available at: https://www.biopasos.com/

Chazdon, R., Wilson, S., Brondizio, E., Guariguata, M., and Helbohn, J. (2021). Key challenges for governing forest and landscape restoration across different contexts. *Land Use Policy* 104:104854. doi: 10.1016/j.landusepol.2020.104854

Coolsaet, B., Martin, A., Armijos, T., Dawson, N., Edwards, G., Few, R., et al. (2020). Environmental justice and transformations to sustainability. *Environ. Sci. Policy Sustain. Dev.* 62, 19–30. doi: 10.1080/00139157.2020.1820294

Enqvist, J., Tengö, M., and Örjad, B. (2020). Are bottom-up approaches good for promoting social–ecological fit in urban landscapes? *Ambio* 49, 49–61. doi: 10.1007/s13280-019-01163-4

FONTAGRO. (2019). Governanza del sistema de conocimiento e innovación en agricultura de los países de Iberoamérica. Presente y futuro. BID. Available at: https://www.fontagro.org/wp-content/uploads/2019/06/gobernanza-del-sistema-08-9-2019.pdf

Government of Mexico. (2023a). Setting the foundations for the transformation of the dairy sector; a challenge to advance in regulations. Available at: https://www.gob.mx/agricultura/prensa/sienta-bases-el-gobierno-para-la-transformacion-del-sector-lechero-un-reto-avanzar-en-la-normatividad?idiom=es

Government of Mexico. (2023b). Livestock sector: Source of employment, economic growth, and combatting malnutrition. Available at: https://www.gob.mx/agricultura/prensa/sector-pecuario-fuente-de-empleos-crecimiento-economico-y-combate-a-la-desnutricion-agricultura?idiom=es

IICA. (2021). Livestock in Mexico has immense potential to contribute to climate change mitigation and adaptation. Available at: https://www.iica.int/en/press/news/livestock-mexico-has-great-potential-contribute-climate-change-mitigation-and-adaptation

Larson, A., and Petkova, E. (2011). An introduction to Forest governance, people and REDD+ in Latin America: obstacles and opportunities. *Forests* 2, 86–111. doi: 10.3390/f2010086

Li, H., Vincent, N., Chancellor, S., and Hecht, B. (2023). The dimensions of data labor: a road map for researchers, activists, and policymakers to empower data producers. FAccT '23: Proceedings of the 2023 ACM Conference on Fairness, Accountability, and Transparency, 1151–1161.

Ostrom, E. (1990). *Governing the commons: The evolution of institutions for collective action. 1st* Edn. Cambridge: Cambridge University Press.

Ostrom, E. (2010a). Polycentric Systems for Coping with collective action and global environmental change. *Glob. Environ. Chang.* 20, 550–557. doi: 10.1016/j.gloenvcha.2010.07.004

Ostrom, E. (2010b). A long polycentric journey. *Annu. Rev. Polit. Sci.* 13, 1–23. doi: 10.1146/annurev.polisci.090808.123259

Ostrom, E. (2014). *Understanding institutional diversity*. Princeton, New Jersey Sikor: Princeton University Press. Available at: https://www.tandfonline.com/doi/full/10.1080/19438150902811897

Petkova, E., Larson, A., and Pacheco, P. (2011). *Governanza forestal y REDD+: Desafíos para las políticas y mercados en América Latina*. Indonesia: Center for International Forestry Research. Available at: https://www.cifor.org/publications/pdf_files/Books/BPetkova1101.pdf

Poteete, A., Janssen, M., and Ostrom, E. (2010). *Working together: Collective action, the commons, and multiple methods in practice*. Available at: https://press.princeton.edu/books/paperback/9780691146041/working-together

Santos, D., Simao, C., and Tomiko, C. (2021). From self-governance to shared governance: institutional change and bricolage in Brazilian extractive reserves. *Environ Sci Policy* 123, 106–113. Available at: https://www.sciencedirect.com/science/article/abs/pii/S1462901121001428

Santos, D., Simao, C., and Trimble, M. (2022). Catalytic and structural factors behind advancements of co-management in protected areas: contributions for its evaluation. *J. Environ. Manag.* 311 Available at: https://www.sciencedirect.com/science/article/abs/pii/S030147972200398X

Sikor, T. (2008). *Public and Private in natural resources governance. A false Dichotomy?* Earthscan publishes.

Sikor, T., Auld, G., Bebbington, A., Benjaminsen, T., Gentry, B., Hunsberger, C., et al. (2013). Global land governance: from territory to flow? *Environ. Sustain.* 5, 522–527. doi: 10.1016/j.cosust.2013.06.006

Tengo, M., Brondizio, E., Elmqvist, T., Malmer, P., and Spierenburg, M. (2014). Connecting diverse knowledge Systems for Enhanced Ecosystem Governance: the multiple evidence base approach. *Perspective* 43, 579–591. doi: 10.1007/s13280-014-0501-3

Tengö, M., Reyes, V., Tofighi, A., Austin, B., Benyei, P., Danielsen, F., et al. (2022). Data sovereignty in community-based environmental monitoring: toward equitable environmental data governance. *BioSicence* 72, 714–717. doi: 10.1093/biosci/biac048

Vásquez Aguilar, A. A. (2023). Livestock and the Loss of Biodiversity. Instituto de Ecología, A.C. (INECOL). Available at: https://www.inecol.mx/inecol/index.php/es/component/content/article/17-ciencia-hoy/845-la-ganaderia-y-la-perdida-de-la-biodiversidad

Vatn, A. (2005). *Institutions and the environment*. Massachusetts: Edward Elgar Publishing Limited.

Vatn, A. (2020). Institutions for sustainability—towards an expanded research program for ecological economics. *Ecol. Econ.* 168:106507. doi: 10.1016/j.ecolecon.2019.106507

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Landscape connectivity in extensive livestock farming: an adaptive approach to the land sharing and land sparing dilemma

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This study investigates the “land sharing” versus “land sparing” dilemma in the context of extensive cattle ranching in Chiapas, Mexico. Employing a comprehensive methodology that synthesizes various systems and uses a normalized matrix for relative priority assessment, we identified several geographic variables as zoning criteria. These criteria encompass the hemerobic index, proximity to structurally intact forests, fire frequency, and terrain slope, aiming to identify areas optimal for conservation. Our results highlight properties with high conservation potential and propose two distinct connectivity scenarios, both excluding currently preserved areas. The analysis focuses on the interplay between connectivity and hemeroby, identifying human-influenced regions within the landscape and emphasizing the importance of tree conservation in agricultural contexts for biodiversity preservation. By tackling the “land sharing” vs. “land sparing” debate, the study underscores the necessity of sustainable livestock practices and the critical role of connectivity in ranching landscapes for ecosystem preservation.

KEYWORDS
livestock, landscape connectivity, AbE, hemeroby, multi-criteria analysis

1 Introduction

Land-use change significantly impacts biodiversity conservation and ecosystem service provision. Studies highlight traditional cattle ranching’s role in the extensive deforestation of tropical dry forests across Latin America, with less than 1.7% of intact forest remaining, thereby threatening biodiversity and ecosystem services within decades due to livestock production expansion (Tscharntke et al., 2005; Harvey et al., 2011; Tobar-López et al., 2019). Although agriculture and livestock are pivotal for food security and economic contributions, notably with livestock farming accounting for 40% of GDP contributions in some countries (Pezo et al., 2019), these sectors are also major biodiversity pressures, leading to deforestation and adversely affecting ecological processes. Daszak et al. (2020) underscores the insufficiency of current actions to adapt to and mitigate climate change’s effects on biodiversity and ecosystem services, emphasizing the need for harmonization between human requirements and biodiversity conservation.

Ecosystem-based Adaptation (EbA) emerges as a promising approach for addressing the impacts of climate change by capitalizing on biodiversity and ecosystem services. Through practices such as silvopastoral systems, EbA fosters ecological and functional connectivity within productive landscapes, simultaneously bolstering climate resilience while conserving biodiversity and facilitating sustainable territorial planning (Harvey et al., 2017). Complementing this approach, the discourse surrounding "Land Sparing" versus "Land Sharing" offers an alternative perspective on sustainability within these landscapes. While "Land Sparing" advocates for the segregation of conservation and production areas to optimize both outputs and conservation efforts, "Land Sharing" seeks to integrate these areas, promoting biodiversity-friendly agricultural practices (Perfecto and Vandermeer, 2012; Fischer et al., 2014). Hemeroby, serving as a crucial ordinal indicator for assessing the impacts of land-use changes on natural systems, plays a vital role in understanding the repercussions of unsustainable land-use intensification on biodiversity and ecosystem services. Insights garnered from hemeroby assessments contribute significantly to informed decision-making for sustainable planning within productive landscapes (Fu et al., 2006; Walz and Stein, 2009; Fehrenbach et al., 2015).

This study aims to evaluate the integration of a connectivity model within an EbA strategy in livestock landscapes, focusing on optimizing environmental services and biodiversity management amidst livestock-induced impacts. We propose developing this model using a multi-criteria evaluation framed within a Hierarchical Analysis Process and a Geographic Information System, addressing criteria such as fire frequency, deforestation, forest degradation, land slope, infrastructure layout, and human intervention (hemeroby). By weighing these criteria based on expert judgment, we aim to identify areas suitable for biodiversity conservation, enhancing forest connectivity and ecological restoration in livestock landscapes.

Finally, this research seeks to address how ecological connectivity models can be integrated into EbA strategies in livestock landscapes, the role of hemeroby as a central indicator in capturing landscape complexities, and its contribution to the Land Sparing" and "Land Sharing debate for biodiversity conservation.

2 Materials and methods

2.1 Area of study

The state of Chiapas, located in southeastern Mexico, is bordered to the north by Tabasco, to the east and south by the Republic of Guatemala, and to the west by the Pacific Ocean, Oaxaca, and Veracruz. With a territorial area of 75,634 km^2, it represents 3.8% of the national territory (Figure 1). Within Chiapas, there are the geographical provinces of the Southern Gulf Coastal Plain, the Sierra Madre de Chiapas, and the Central American Cordillera. The terrain is mostly composed of mountain ranges, which include sedimentary rocks. The southeast of the state is home to the highest altitudes, highlighting the Mozotal hill with 3,050 meters above sea level and the Tacaná volcano with 3,284 meters above sea level, on the border with Guatemala. In the central region there are valleys and canyons, such as the Sumidero Canyon, crossed by the Grijalva River. To the north, there is a ridge with plains shared with Tabasco, while to the south there is a coastal plain formed by fluvial and marine deposits. Climatically, 54% of Chiapas has a warm humid climate, 40% warm sub-humid, 3% humid temperate and the remaining 3% sub-humid temperate.

In terms of land use, agriculture and pastures predominate. Irrigated and rainfed agriculture covers 10.7% of the state (804,000 ha); pastures account for 19.2% (1,438,279 ha). Temperate forests in a good state of conservation occupy 14% (1,049,500 ha), while those with some degree of alteration cover 4.5% (341,150 ha). Mesophilic mountain forests, of great biological importance, comprise 5.4% (405,280 ha), and mosaics of these forests with secondary vegetation, 3.5% (262,000 ha). Tropical forests in good condition and with some degree of alteration have similar percentages, 19.3% (1,444,000 ha) and 19.2% (1,439,000 ha), respectively (Jiménez Trujillo et al., 2020).

In Chiapas, cattle ranching is a predominant agricultural activity, particularly characterized by extensive dual-purpose cattle production. The region's cattle ranching occupies approximately 3,059,531 hectares, averaging 8.6 hectares per production unit. This area accounts for 6.37% of the national territory dedicated to such activity, with 88.5% of these units classified as small-scale operations (INEGI, 2013).

However, this economic activity contributes significantly to environmental challenges in the region. It is a major driver of deforestation and tree cover loss, leading to a myriad of ecological issues. These include diminished soil fertility, heightened greenhouse gas emissions, reduced water availability and quality, and a decrease in biodiversity. Such impacts are particularly pronounced in areas experiencing the expansion of the livestock frontier (Jiménez Trujillo et al., 2020).

2.2 Methodological structure

This study employs an integrated systems modeling framework where the outputs from certain systems serve as inputs or parameters for others, as illustrated in Figure 2. The methodology unfolds in distinct phases, beginning with the identification and definition of geographic variables for zoning purposes. The objective is to delineate areas eligible for conservation efforts. The selected zoning criteria encompass the hemerobic index, proximity to structurally preserved forests, fire frequency over the past decade, and terrain slope. Additionally, terrestrial communication routes and land cover data feed into the hemerobic index calculation.

Land cover classification leverages satellite imagery through the Random Forest algorithm, a machine learning technique that constructs multiple decision trees on random data subsets with bootstrapping. This approach, known for balancing high variance against low bias, finalizes classifications based on the averaged probabilities across all trees, thereby enhancing model robustness against extreme values and reducing the risk of overfitting (Pal, 2005; Akar and Güngör, 2012; Belgiu and Dragut, 2016).

The processing of satellite images from Sentinel-1 and -2 datasets was conducted on the Google Earth Engine (GEE) platform. GEE, known for its vast storage of remote sensing data and its capability for automated parallel computing, significantly outperforms local processing by accessing a planetary-scale repository of imagery. This platform supports a broad array of functions, which users can apply flexibly using programming languages such as Python or JavaScript. The methodological choice of GEE leverages its computational efficiency and the diverse functionality it offers for remote sensing

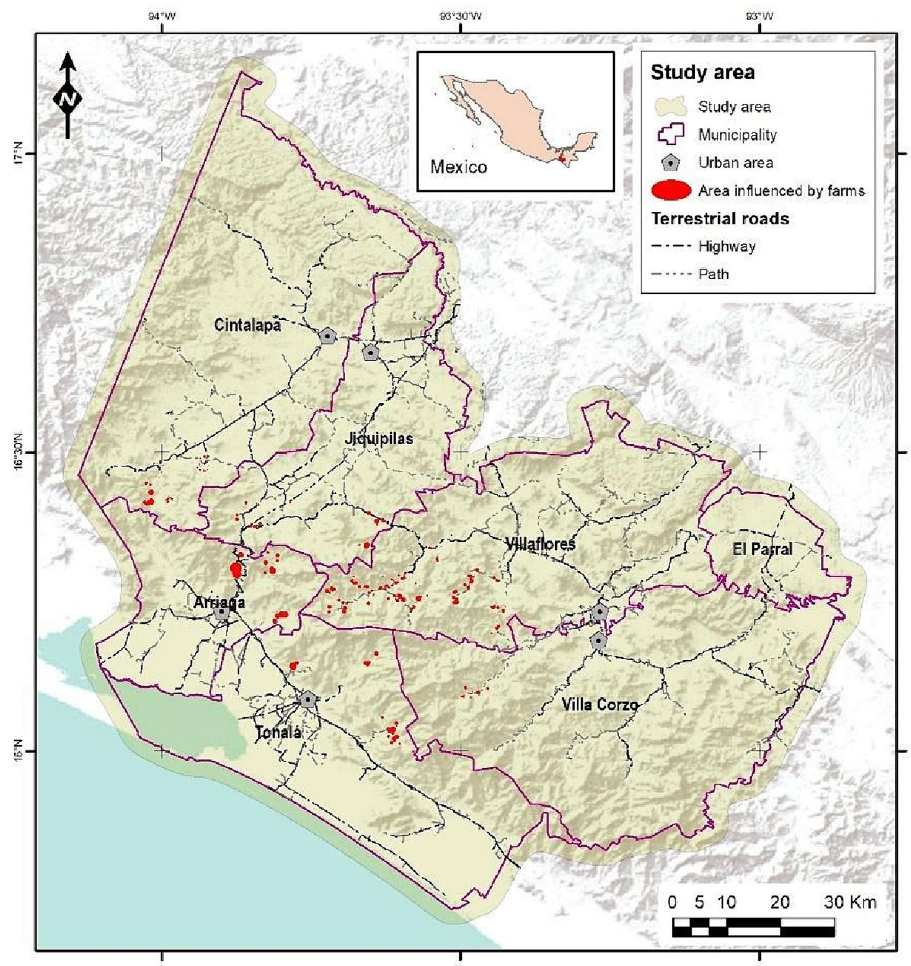

FIGURE 1
Geographic overview of Chiapas, Mexico: the study area in context.

analysis, aligning with established protocols and enhancing the reproducibility of the classification process (Reiche et al., 2016; Gorelick et al., 2017; Kumar and Mutanga, 2018; Mutanga and Kumar, 2019).

The methodology for zoning potential conservation areas initiated with the transformation of geographic variables into a raster format, standardizing values between zero and one to ensure a uniform, dimensionless numerical scale conducive to comparison and integration based on conservation relevance. Subsequently, a Multicriteria Assessment (MCA), comprising a suite of techniques to aid in the evaluation process, was employed to weigh different criteria according to the researcher's preferences and construct scenarios that mitigate uncertainty in assessing alternatives. Within this framework, the Hierarchical Analysis Process (AHP) was utilized, a method within the MCA that facilitates the inclusion of various aspects into the conservation zoning model by recognizing the interrelations among alternatives in relation to a set of attributes. The AHP methodology unfolded in three stages: first, the modeling or structuring of relevant variables for the evaluation to ensure comprehensive consideration of pertinent factors; second, the assessment or incorporation of evaluators' preferences through established judgments in a matrix of paired comparisons, permitting a systematic evaluation of criteria based on their significance; and third, the prioritization or calculation of the weight vector of the criteria considered in the evaluation. This weight vector was subsequently integrated into the geographic criteria in raster format, aiming to extract pertinent information for the zoning of conservation areas, following guidance from foundational works in the fields of MCA and AHP (Jiménez, 2002; Fülöp, 2004; Gómez and Barredo, 2006; Malczewski, 2006).

2.2.1 Ground covers

The coverage cartographic layer was generated based on a classification of optical and Synthetic Aperture Radar (SAR) images obtained during 2021, implementing the *Random Forest* technique. The optical images corresponded to a mosaic of *Sentinel-2* products (MSI Level 2A collection, available from GEE) at a spatial resolution of 10–20 m. The visual spectrum (RGB) and near-infrared (NIR) bands were included, which contain the most relevant information to differentiate the types of vegetation cover (Singh, 1987; Baeza et al., 2006; Serbin and Townsend, 2020). A function based on the SCL band was implemented, which allowed masking shadows and clouds to later calculate a mosaic with the average of the pixel values. A vegetation index was calculated and added to the model, corresponding to the

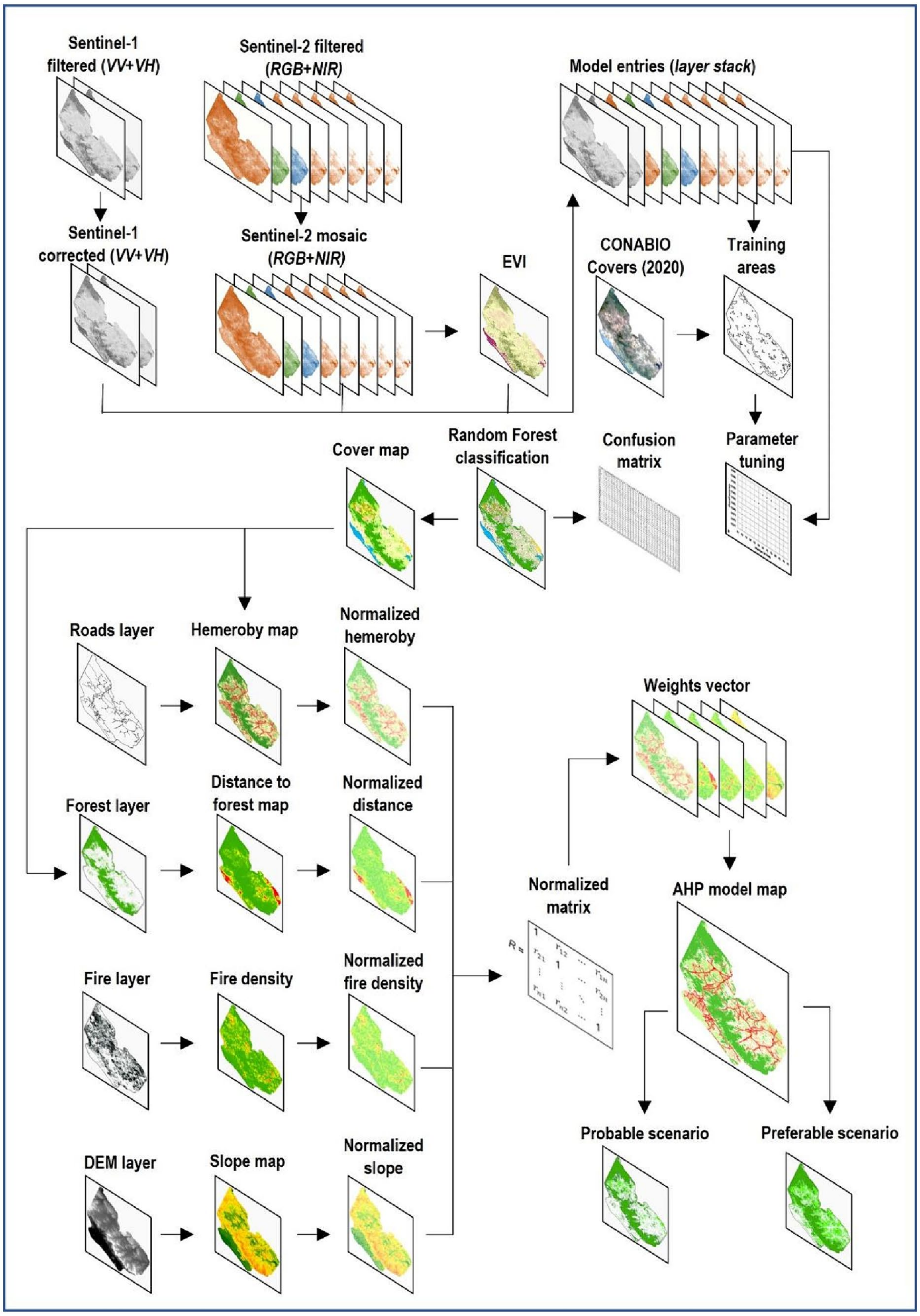

FIGURE 2
Methodological structure based on integrative modeling approach.

Enhanced Vegetation Index (EVI), which allowed to partially suppress the influence of lighting, terrain heterogeneity and soil reflectance on the image data (Singh, 1987; Baeza et al., 2006; Tsai et al., 2018; Serbin and Townsend, 2020).

The SAR images implemented during the coverage classification corresponded to *Sentinel-1* products (S1 GRD collection, available in GEE) at a spatial resolution of 10 m. VV and VH polarizations were included in interferometric wide-band mode and descending orbit. Speckel correction was performed with the average of the pixel values (Raed et al., 1996) with the average focal length filter at 50 m to increase the accuracy of the image classification (Waske and Braun, 2009). The bands from the optical and SAR sensors were co-registered with respect to the lowest spatial resolution mosaic *Sentinel-2* and stacked into a single multi-sensor image.

The performance of a supervised classification of satellite imagery depends on both the robustness of the classifier and the quality of the training samples, which unambiguously represent the land cover categories on the multi-sensor image (Olofsson et al., 2014). The assignment of training areas considered the spectral amplitude of the multi-sensor image and the landscape representativeness of the classes, since the balanced samples between the thematic categories present greater accuracy by reducing the error of commission and omission of the underrepresented classes (Jin et al., 2014; Tsai et al., 2018). The pixels included in the training areas were divided into 70% for the *Random Forest* classification and the remaining 30% for the calculation of the modeling accuracy (Azzari and Lobell, 2017), which ensured the statistical independence of the validation data and limited the overestimation of the model's accuracy (Congalton, 1991; Belgiu and Dragut, 2016). The training areas of the cover model were obtained by visual adjustment on the multisensor image of representative areas adapted from the land cover cartographic layer of Mexico at 30 m (CONABIO, 2020).

In theory, it is assumed that a higher number of decision trees in the *Random Forest* classification increases the fit of the model, although it also increases the processing time linearly, which justifies the calculation of the optimal number of decision trees (Probst et al., 2019). In addition to the number of decision trees, the classifiers were configured with the sampling variables defined by the multi-sensor image and the vectors representing the training areas, whose thematic attributes should be set as integers. The samples were then divided into 70% for training and 30% for accuracy estimation, through an iterative function in a sequence of every 10 trees until 140 trees were completed. Finally, predictions were made according to the sampling variable and the sequential parameters of the trees, with which the accuracy was plotted according to the number of trees in the classification.

The final *Random Forest* classification and error calculation were configured with the same training variables and the number of decision trees that obtained greater accuracy during parameter tuning (Pal, 2005). The results of the classification were exported in raster format at a spatial scale like the multisensor image (20 m), the thematic raster obtained was generalized to a scale of one ha, grouping pixels in homogeneous areas, and replacing values with less representativeness for those of adjacent groups that reached the defined area. Generalization includes the processes of "thematic aggregation," which aggregates adjacent similar pixels and creates larger pixels, according to a majority focal filter applied to a moving window of predefined size (2×2); "clump" identifies groups of contiguous pixels of each thematic class, based on an attribute table assigned in the previous process and according to a number of adjacent pixels (8); "Eliminate" iteratively performs a focal majority filter, so that the values of pixels grouped in areas smaller than one ha are replaced by values of surrounding areas that meet the required number of pixels.

The estimation of the error associated with the classification was calculated with the same training variables of the *Random Forest* models, together with the number of previously defined classification trees (Pal, 2005). The training areas were divided in a similar way to the parameterization procedures (70–30%). Accuracy estimates included the confounding matrix, overall model accuracy, and Kappa coefficient. The confusion matrix is a square array, whose diagonal indicates the pixels that were correctly classified within the sample (Liu et al., 2007) This matrix allows you to evaluate the overall accuracy of the classification, calculated as the ratio between the number of correctly classified pixels and the total number of pixels in the sample. The *Kappa* coefficient is defined as an estimate of the difference between the accuracy achieved by the automatic classifier and a random classification (Rosenfield and Fitzpatrick-Lins, 1986; Plourde and Congalton, 2003).

2.2.2 Hemeroby index

The hemeroby index is a comprehensive estimator of human impact on natural systems, considering the relationship between current land use and vegetation that would exist in the absence of anthropogenic disturbances (Steinhardt et al., 1999; Peterseil et al., 2004; Niño et al., 2023). This indicator shows imbalances between conservation areas and land use planning, points out areas that require measures to improve the environmental conditions of the landscape and highlights the progress of environmental management (Walz and Stein, 2009). These imbalances could indicate the differential use of ecosystem services in densely populated areas, whose demand is proportional to the established human population and where natural areas are transformed to maximize certain services to the detriment of others (Schneiders and Müller, 2017).

To map the geographical distribution of hemerobic levels, we integrated geographic information from the BioPaSOS project's road mapping (INEGI, 2019). This process involved creating buffers of 0.4 km around main roads and 0.2 km around secondary roads, represented by line-type vectors. The buffers were overlaid onto the land use layer to delineate areas of influence adjacent to roads. Subsequently, the nominal classes resulting from this cartographic integration were converted into numerical ordinal categories, ranging from zero (representing the lowest degree of human intervention) to one (indicating the highest degree of human intervention) (Table 1). This reclassification was based on the compilation and assignment of hemeroby levels to different land uses, following the methodologies proposed by Steinhardt et al. (1999) and Walz and Stein (2009).

2.2.3 Distance to forests, fire hotspots and slope.

The criterion of distance to forests was established with the creation of a raster, whose values correspond to the Euclidean distance between the center of each pixel and the nearest area covered by structurally preserved forest, according to the cartographic layer of

TABLE 1 Levels of Hemeroby based on reclassification of coverage and areas influenced by roads.

Degree of hemeroby	Description
Ahemerobic	Almost no human impacts. No representation in the study area.
Oligohemerobic	Weak human impacts. Includes forest, natural scrub, and natural grassland.
Mesohemerobic	Moderate human impacts. Includes intervened forest and water bodies.
β-euhemerobic	Moderate-strong human impacts. Includes pastureland.
α-euhemerobic	Strong human impacts. Includes crop land.
Polyhemerobic	Very strong human impacts. Includes bare ground.
Metahemerobic	Excessively strong human impacts; biocoenosis destroyed. Includes artificial land and areas influenced by roads.

Adapted from Walz and Stein (2009).

covers. It was assumed that the greater the distance from the forest, the lower the suitability of a locality for conservation, so the inverse of the data of the magnitude of the distance was calculated, to later be transformed to a scale of zero to one through a linear function.

The criterion of fire outbreaks was calculated according to the frequency of these events, recorded in point-type vector format, by the Fire Information for Resource Management System (FIRMS) program, in the study area during the last decade (NASA, 2023). A raster with the count of events within a radius of 1 km was created by implementing a kernel function to obtain a smoothed image. Since the inverse relationship of fire density with the conservation fitness of a locality was assumed, the inverse of the data was calculated before transforming the variable to the scale of zero to one.

The slope criterion of the terrain was calculated based on a Digital Elevation Model of Mexico at a scale of 15 m (INEGI, 2013). The slope in percentage was identified by calculating the proportion of change in the value of each pixel toward the surrounding neighbors. For this criterion, it was assumed that it is directly related to the conservation suitability of a locality, since the steeper the slope, the lower the willingness to establish human activities on its surface.

2.2.4 Hierarchical analysis process (AHP)

The synergy between Geographic Information Systems (GIS) and AHP has been recognized for its substantial efficacy in territorial evaluation and decision-making processes. This combined approach leverages geographic information technologies, enabling evaluators and policymakers to apply these tools across various applications, including policy formulation, development of scenarios, and prioritization of conservation areas. A significant advantage of integrating GIS with AHP is the ability to embed decision-makers' value judgments into the analysis (Equation 1). This process not only allows for the nuanced weighting of criteria and assessment of alternatives but also facilitates a deeper comprehension of policy evaluation implications. The integration thus significantly bolsters the reliability and acceptance of the resulting decisions (Malczewski, 2006).

The Analytic Hierarchy Process (AHP) methodology is delineated into three sequential stages: (1) Modeling, where the decision-making process's relevant aspects are systematically structured; (2) Valuation, entailing the assessment of decision-makers' or evaluators' preferences through a matrix of paired comparisons; and (3) Prioritization, which establishes the criteria's weight vector crucial for solving the problem at hand (Niño, 2019).

The weights of the criteria were estimated using the Saaty method (Saaty, 1994), which is a procedure that quantifies the evaluator's preferences with respect to the relative importance of each of the criteria included in the AHP. The objective of the method is to construct a vector of priorities or weights that allows the hierarchical and numerical evaluation of the criteria under consideration. Initially, a square matrix was configured with paired comparisons, which describes a scale that defines the correspondence between the evaluator's qualitative assessment and a numerical assignment (Saaty and Shang, 2011). Subsequently, the normalized matrix was calculated following the methodological guidelines and theoretical considerations presented by Niño (2017, 2019), with which the weight vector of the criteria considered in the evaluation of the suitability of areas susceptible to be released for conservation purposes was estimated. Once the weight vector was obtained, the weighting of each criterion was carried out according to the assigned weight, which corresponds to the product of these values in each of the alternatives or pixels of the raster cartographic layers and representing the spatialized variables included in the evaluation. Next, a weighted linear summation was performed, in which a single value of suitability for conservation was obtained with the sum of the values of the adjusted criteria, according to the weight assigned to each variable.

Given that weights are determined based on the subjectivity of a decision-maker or expert and the exact weights remain unknown, the matrix incorporates errors about the true weights. Hence, it is essential to evaluate the consistency level of the assigned weights. Should the consistency level prove to be unacceptable, the decision-maker must revisit and amend judgments on prior comparisons before advancing with the analysis. The matrix R is characterized by a rank of 1 due to its reciprocal condition and exhibits an eigenvalue different from zero (λ), notable for producing a scalar multiple of itself upon transformation. Consequently, the sum of a matrix's eigenvalues equals the sum of its main diagonal values, with all elements equaling 1. It thus can be asserted that the non-zero eigenvalue of the true weight matrix equals the dimension of the square matrix, that is, n ($\lambda = n$). Discrepancies within the matrix R can lead to non-zero values, making the maximum value of λ (λmax) associated with an eigenvector deemed an approximation to the weight vector ŵ (Jiménez, 2002; Alonso and Lamata, 2006), whose mathematical representation is:

$$R * \hat{w} = \lambda_{\max} * \hat{w} \quad (1)$$

Subsequently, the degree of inconsistency in the decision-maker's judgments regarding the weighting will be assessed using the IC Consistency Index (Equations 2, 3).

$$IC = \frac{\lambda_{\max^{-n}}}{(n-1)} = \frac{1}{n(n-1)} \sum_{i=j}^{n} \left(e_{ij} - 1\right) \quad (2)$$

Where $e_{ij} = \frac{w_j}{w_i}$

The Consistency Index (CI) can be computed using the Random Consistency Index (RI), which is derived from simulating 500,000 randomly generated Saaty reciprocal matrices. The ratio of CI to RI estimates the Consistency Ratio (CR):

$$RC = \frac{IC}{IA} \quad (3)$$

Considering the value of RC, the matrix R is deemed completely consistent if $RC = 0$. The matrix R exhibits an acceptable level of inconsistency, and the weight vector is considered valid if $RC \leq 0.1$. Conversely, it is deemed inadmissible if $RC > 0.1$.

3 Results

The parameterization of the coverage classifier showed that with 140 decision trees, the highest accuracy of the model was achieved, calculated at 0.9993; that is, that 99.93% of the pixels classified in the training areas coincided with the categories defined in the sample. The calculation of the Kappa coefficient allowed us to establish the probability of performing a correct classification at 0.9990, compared to a classifier that randomly assigns pixels to the different classes of coverage. The coverage results show that conserved forests predominate with 37.26% of the area of interest, followed by intervened forests (30.18%). Among the agricultural areas, pastures introduced for livestock (15.04%) predominate over agricultural areas (4.07%). It is evident that 20% of the study area has been drastically transformed by anthropogenic activities (Figure 3).

The map of hemerobic levels (HMRB) (Figure 4) presents in detail the diversity of human impact on the landscape of the study area. The oligohemerobic level predominates with 41.95% of the territory studied, characterized by natural areas of forests, shrubs, and grasslands. This is followed to a lesser extent (33.20%) by areas with a mesohemiobic level, whose predominant coverage corresponds to intervened forests that have lost their original structure; areas with a β-euhemerobic level (11.53%), occupied by introduced pastures dedicated to livestock; areas with a metahemerobic level (10.05%), used by urban infrastructures and areas influenced by land transit routes; areas of α-euhemerobic level (3.03%), where areas dedicated to agricultural activities predominate; and with the smallest extension, the areas with polyhemerobic level, occupied by bare soils (see definitions of levels in Table 1).

According to the FIRMS program, 61,210 fire events (FF) were detected in the study area over the past decade. Per square kilometer, there were an average of 4.76 fires, with a maximum of 90 events and a standard deviation of 5.87 (Figure 5). The matrix of distances to the nearest forested areas (DBC) showed that the areas devoid of this cover are on average 678.86 m from the conserved forests, with a maximum distance of 12,466.87 m and a standard deviation of 1,237.13 (Figure 6). The predominant slopes (SLP) in the study area, with 25.83% of the territory, correspond to the slightly steep ones, whose range in percentage of inclination ranges from 25 to 50. It is followed in distribution (20.55%) by strongly inclined slopes with percentages between 12 and 25%; slightly inclined slopes (3 to 7% slope) occupying 15.79% of the area; and flat areas (0 to 3% slope) with 14.62% of the territory (Figure 7).

Table 2 shows the normalized matrix, with which the weight vector of the criteria considered in the evaluation of the suitability of areas susceptible to being released for conservation purposes was calculated. The degree of inconsistency of the decision-maker's judgments was estimated with the Consistency Index, where the

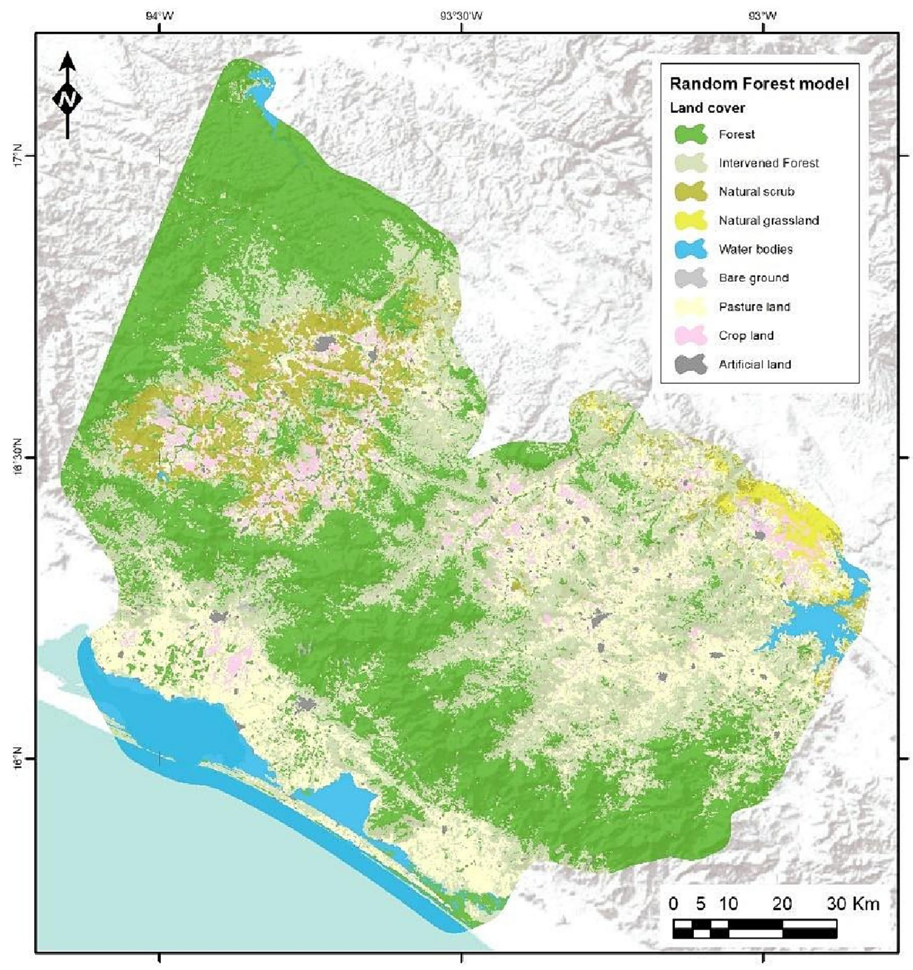

FIGURE 3
Land cover classification: insights from Random Forest analysis of optical and SAR imagery.

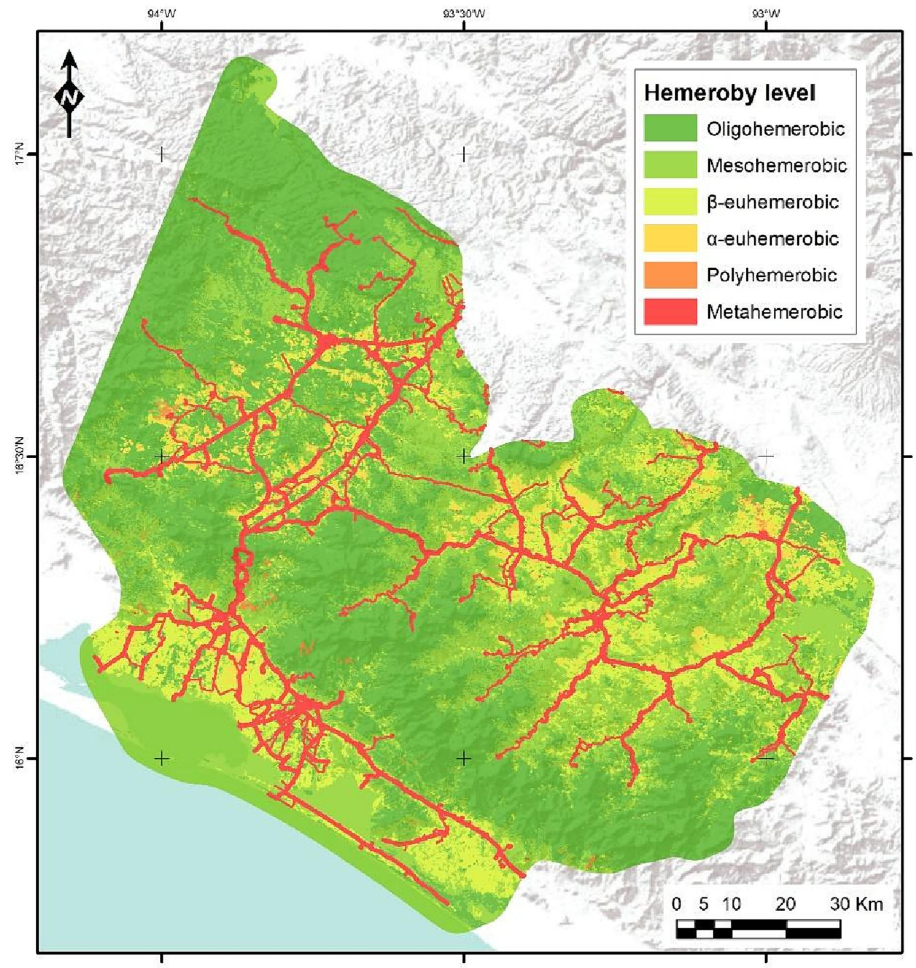

FIGURE 4
Hemeroby index based on reclassification of geographic information on land covers and terrestrial roads. See Table 1 for explanations on hemeroby levels.

average of the eigenvalue λ (4.118) indicated congruent evaluations in the normalized priority matrix, since its values were close to and never less than the number of criteria (four); the calculated Consistency Index was 0.039, which was later computed, in the calculation of the Consistency Ratio, with a Random Consistency Index corresponding to 0.882, which figure is reported by Alonso and Lamata (2006) implementing 500,000 random matrices for four criteria. The resulting Consistency Ratio was 0.045, a value less than 0.1, so the weight vector is considered to have an admissible inconsistency.

According to the vector of weights, the conservation suitability was calculated with a map algebra geoprocess, on the raster-type cartographic layers of the criteria considered and according to the expression:

$$Suitability = \left(HMBR * 0{,}56\right) + + \left(DBC * 0{,}26\right) + \left(FF * 0{,}12\right) + \left(SLP * 0{,}06\right)$$

Once the weight vector was integrated into the geographic information of the criteria, a cartographic output of the spatial distribution of the territory's conservation suitability was obtained (Figure 8), which allows us to distinguish the areas with the greatest disposition to be released for conservation purposes. According to the AHP model, areas with very high suitability for conservation predominate with 36.01% of the territory, followed by areas with medium suitability with 25.42% and those with high suitability with 15.90%. To a lesser extent, there are areas with low and very low conservation suitability, with 13.30 and 9.29% of the territory, respectively.

With respect to the farms intervened in the study area and its area of influence, the highest proportion of properties (28.53%) are mostly in areas of medium suitability for conservation and with an area of influence of 1,281.60 ha, followed by properties in very low suitability (25.96%) with 1,367.28 ha and properties in very high suitability (23.08%) with 1,577.16 ha. To a lesser extent, there are properties in high (12.82%) and very low (9.61%) suitability, with areas of influence of 541.48 ha and 302.40 ha, respectively.

According to the level of suitability for conservation calculated with the AHP model, two connectivity scenarios were defined that excluded the areas that are currently covered by conserved forests. The probable connectivity scenario (Figure 9) includes the very high and high suitability categories, this scenario includes mostly 20.19% of the properties of interest, with an area of influence of 587.52 ha. The

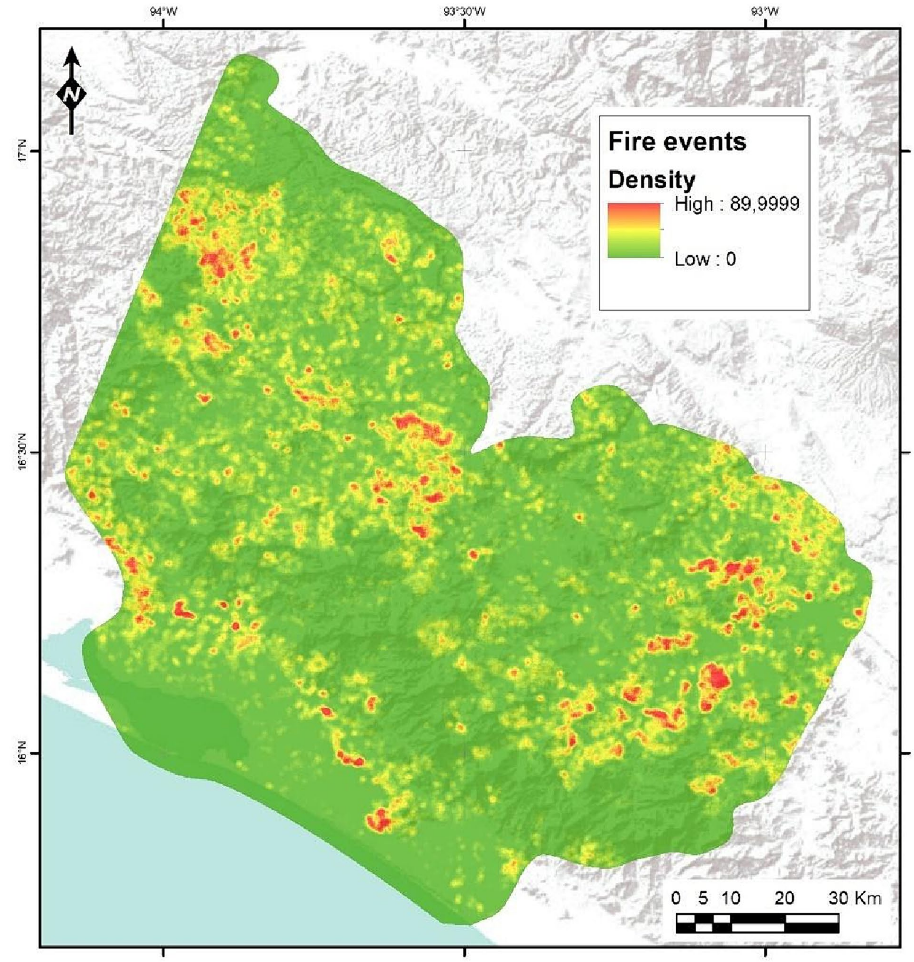

FIGURE 5
Fire hotspots per km^2 based on frequency events registered by FIRMS program during last decade.

preferable connectivity scenario (Figure 10), in addition to the categories included in the likely scenario, includes the areas of average fitness. This scenario covers mostly 55.77% of the farms of interest, with an area of 1,807.92 ha.

4 Discussion

4.1 Integration or separation of land for biodiversity conservation in livestock landscapes

The approach of "Land Sparing" versus "Land Sharing" is a central debate in conservation and agricultural production. These approaches have direct implications for how hemeroby and landscape connectivity are managed in livestock and conservation contexts.

An indicator such as hemeroby can contribute to the planning and management of productive landscapes regardless of the approach taken to the distribution of uses in landscapes, i.e., if it is determined to work with Land Sparing, the areas destined for production would have a high hemerobic, while the conservation areas would have a low hemerobic. This creates a clearly defined landscape in terms of human influence; whereas, if the Land Sharing approach is addressed, a large part of the landscape would have an average hemeroby. Agricultural and livestock practices would be adapted to minimize their impact, allowing certain natural features to persist.

Under this approach, we can identify some advantages for both approaches, on the one hand for the Land sparing approach, the conservation of large areas of intact habitat is allowed, essential for species that require large territories or that are sensitive to disturbances; while for Land Sharing, biodiversity is favored in productive landscapes and may be more feasible in areas where it is not possible to clearly separate production from conservation areas.

Sustainable livestock farming is presented as a solution that seeks to balance production demands with the need to conserve biodiversity. In this scenario, intensive production areas would have a high hemerobic rate, while conservation areas would maintain a low hemeroby (Fischer et al., 2014). However, this approach requires ensuring connectivity between conservation areas to maintain ecosystem resilience.

Alternatively, the Land Sharing model advocates for landscapes that incorporate sustainable livestock farming in line with Ecosystem-based Adaptation (EbA) principles, promoting landscapes that are both resilient and interconnected, with a balanced level of human

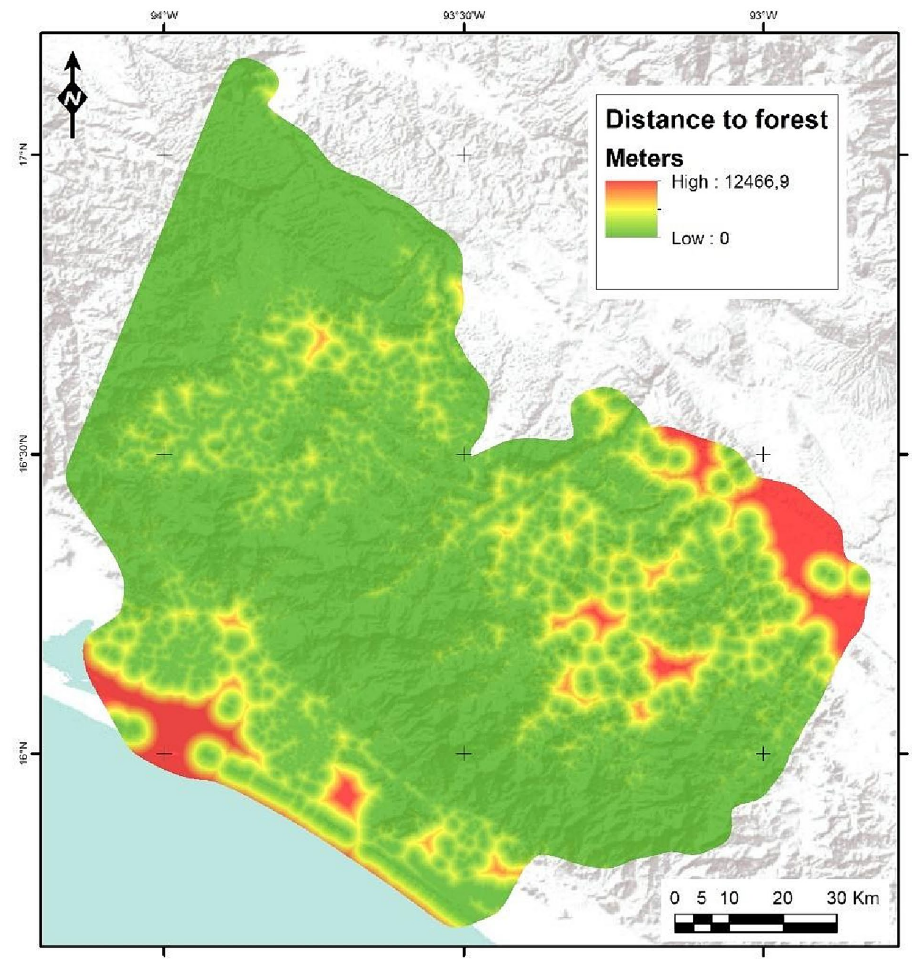

FIGURE 6
Distance to forest as Euclidean distance from deforested areas to nearest area covered by structurally preserved forest.

disturbance. These landscapes, through the harmonization of farming practices and natural elements, are capable of enhancing both agricultural productivity and biodiversity (Estrada-Carmona et al., 2022).

Perfecto and Vandermeer, 2012, Fischer et al., 2014 argue that both separation and integration have roles in biodiversity conservation, and the choice between these approaches may depend on the local context. However, it is clear that complex agricultural landscapes, which integrate multiple land uses and management practices, can be rich in biodiversity and offer multiple ecosystem services. Therefore, promoting complexity and diversity in humanized landscapes can be a key strategy for conservation and ecosystem-based adaptation.

The debate between Land Sparing and Land Sharing is essential in this context. Neyret et al. (2021) found that it is possible to minimize trade-offs between agricultural production and biodiversity conservation through landscape-level strategies. These strategies can be informed by hemeroby, providing guidance on where interventions are required.

Ecosystem-based adaptation (EbA) focuses on strengthening the resilience of ecosystems to challenges such as climate change. In this context, hemeroby can guide landscape management, identifying key areas for connectivity and adapting livestock practices to minimize their impact on biodiversity. A well-connected landscape with sustainable livestock practices can provide essential ecosystem services, benefiting both nature and human communities (Perfecto and Vandermeer, 2012).

4.2 Hemeroby, as the central indicator of a connectivity model, can encompass landscape complexity that includes livestock activity

Indices such as hemeroby provide insights into the condition of ecological systems, aid in decision-making, and contribute to the monitoring and evaluation of political and administrative strategies (Steinhardt et al., 1999). Hemeroby is a measure of landscape heterogeneity in terms of ecological sustainability and is acknowledged as a crucial indicator of biodiversity at the landscape level (Peterseil et al., 2004). Additionally, it is recognized as a comprehensive concept, offering methodological aspects for comparing landscapes (Steinhardt et al., 1999; Fehrenbach et al., 2015).

In practical terms, applying adaptive management using hemeroby as an indicator, where livestock farmers can adapt their

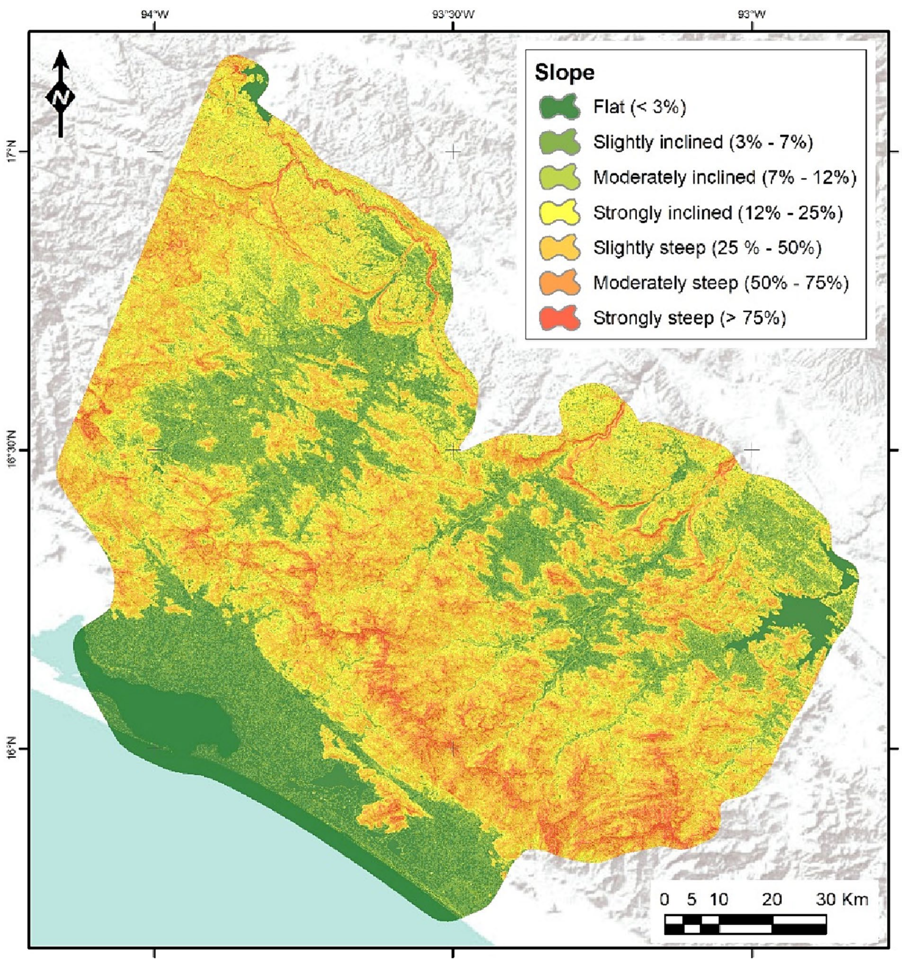

FIGURE 7
Slope levels as a classification of terrain inclination in percentage.

TABLE 2 Standardized priority matrix.

	Predominant slopes (SLP)	Fire events (FF)	Distances to the nearest forest (DBC)	Hemerobic levels (HMRB)	Weight	Weighting	Eigenvalue (λ)
Predominant slopes (SLP)	1	0,33	0,2	0,14	0,06	0,23	4,04
Fire events (FF)	3	1	0,33	0,2	0,12	0,492	4,04
Distances to the nearest forest (DBC)	5	3	1	0,33	0,26	1,099	4,17
Hemerobic levels (HMRB)	7	5	3	1	0,56	2,356	4,22

practices to minimize their impact on key areas for biodiversity, can be very useful for livestock management, as well as for the development of a biodiversity conservation strategy and a better use of resources (Niño et al., 2023). For example, they may avoid grazing in areas of low hemeroby during certain times of the year to protect breeding species (Figure 4).

4.3 Connectivity model in a livestock landscape integrated into an ecosystem-based adaptation strategy

The maintenance of both structural and functional connectivity in livestock landscapes through hemeroby management can contribute

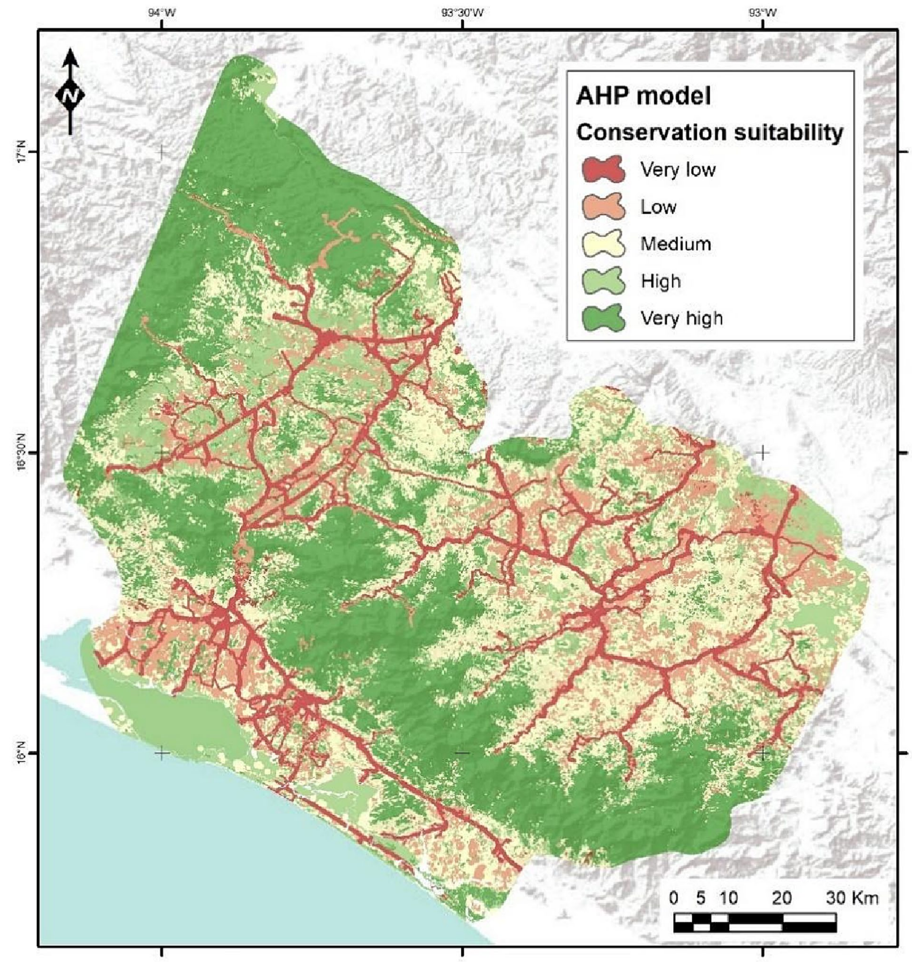

FIGURE 8
Conservation prioritization: identifying key areas through AHP-weighted criteria.

to improving the resilience of these landscapes as well as of the livestock production systems involved, allowing species to move and adapt to changing conditions and at the same time generate conditions that support activities and aspects of livestock systems.

In this sense, a well-connected landscape with sustainable livestock farming can provide essential ecosystem services, such as pollination, pest control and water regulation, which benefit both nature and livestock production systems. Additionally, in livestock landscapes, it is essential to maintain connectivity to allow the movement of species and maintain healthy populations. Hemeroby can help identify areas where livestock has fragmented the landscape and where connectivity corridors are needed (Figure 9).

The relationship between connectivity and Hemeroby is established since the latter allows the identification of areas of high, medium, and low human influence in a landscape (Figure 4). Where, areas of low hemerobics, which have minimal human influence, can act as refuges for biodiversity. Areas of medium hemeroby, which have some human influence but still retain natural features, can act as connectivity corridors between refuge areas (Figures 4, 8–10).

Hemeroby proves its utility in evaluating landscape connectivity and human impact. This is a significant advantage over other methodologies that might not simultaneously consider these aspects. The criticality of incorporating the degree of human disturbance (hemeroby) in landscape connectivity assessments is emphasized, marking an advantage over methods that might overlook this crucial factor.

Contrary to some methods that primarily focus on intrinsic vegetation characteristics or environmental factors, hemeroby places particular emphasis on the extent of human influence, ranging from entirely natural to completely altered environments at various scales. This comparison can underscore the applicability or relevance of hemeroby in specific contexts, particularly in areas where human impact significantly affects vegetation conditions.

Tree conservation in agricultural landscapes, especially in tropical regions, is essential to maintain biodiversity and ecosystem services. Harvey et al. (2011) highlight that these trees provide key resources for many species. However, grassland management practices often threaten the conservation of these trees, underscoring the need for sustainable agricultural practices.

According to an ongoing analysis of tree cover change using EVI as a proxy measuring absolute changes I in the period 2016–2021 (EVI2021 - EVI2016), it was observed that in the state of Chiapas there was a loss in vegetation vigor (assumed as loss of tree cover) with −0.0434 (Figure 11). Although it was determined from the analysis

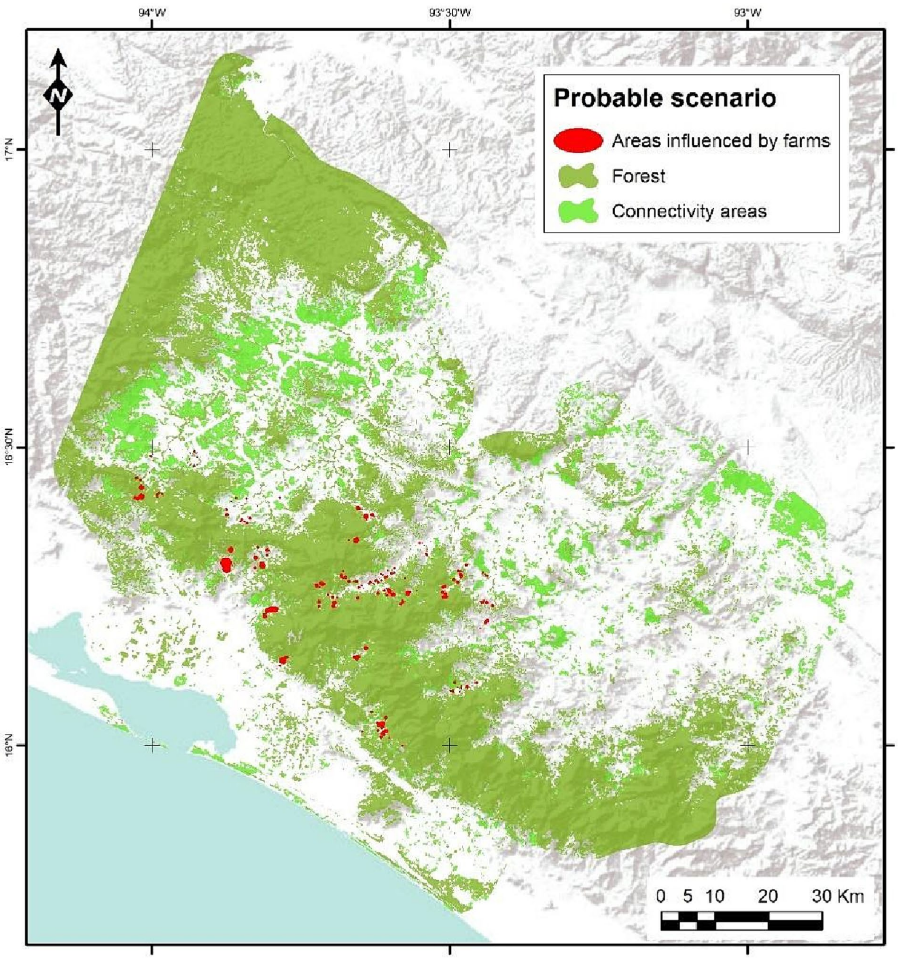

FIGURE 9
Probable scenario for conservation: integrating high and very high suitability areas under AHP analysis.

that deforestation predominates in the territory, in some farms where sustainable practices were implemented, vegetation is maintained and in others the vigor of the vegetation increases (Figure 11).

In summary, in the context of sustainable livestock farming, biodiversity conservation and EbA, Hemeroby can offer insights on how agricultural practices impact landscape connectivity, since this indicator allows us to identify areas with this priority for the intervention of sustainable livestock practices both to maintain the health of ecosystems, Strengthen the resilience of the landscape and communities to climate change. Moreover, hemeroby enables mapping to evaluate and compare landscape quality using an ordinal numerical scale. This is crucial for understanding the impact of human activities on landscape quality.

5 Conclusion

The approach of Ecosystem-based Adaptation from a landscape approach, as a first step in the development of sustainable livestock projects is desirable and necessary, in order to give an initial guideline or guidelines that allow identifying the specific sustainable practices to be implemented in the territory, since one of the gaps in the implementation of the practices is that they are already carried out at the farm level. However, the approach at the landscape level is left aside or for the end of the studies, often ignoring the ecological structure and functionality of the landscape and therefore of the territory.

Hemerobics, along with a deep understanding of sustainable agricultural practices and conservation approaches, can guide effective strategies for biodiversity conservation and ecosystem-based adaptation in agricultural landscapes. The integration of these elements is essential for a sustainable and resilient future.

Using this index offers a unique perspective on how livestock and conservation can coexist. The choice between the Land Sparing and Land Sharing approaches and their relationship to Hemeroby will depend on the local context and the specific characteristics of the landscape. However, in both cases, it is essential to consider landscape connectivity and ecosystem resilience to ensure a balance between livestock production and biodiversity conservation.

The Hemeroby index makes it possible to identify key areas for connectivity and thus adapt livestock practices according to hemeroby, leading to a sustainable livestock model that benefits both biodiversity and human communities, aligning with the principles of Ecosystem-based Adaptation.

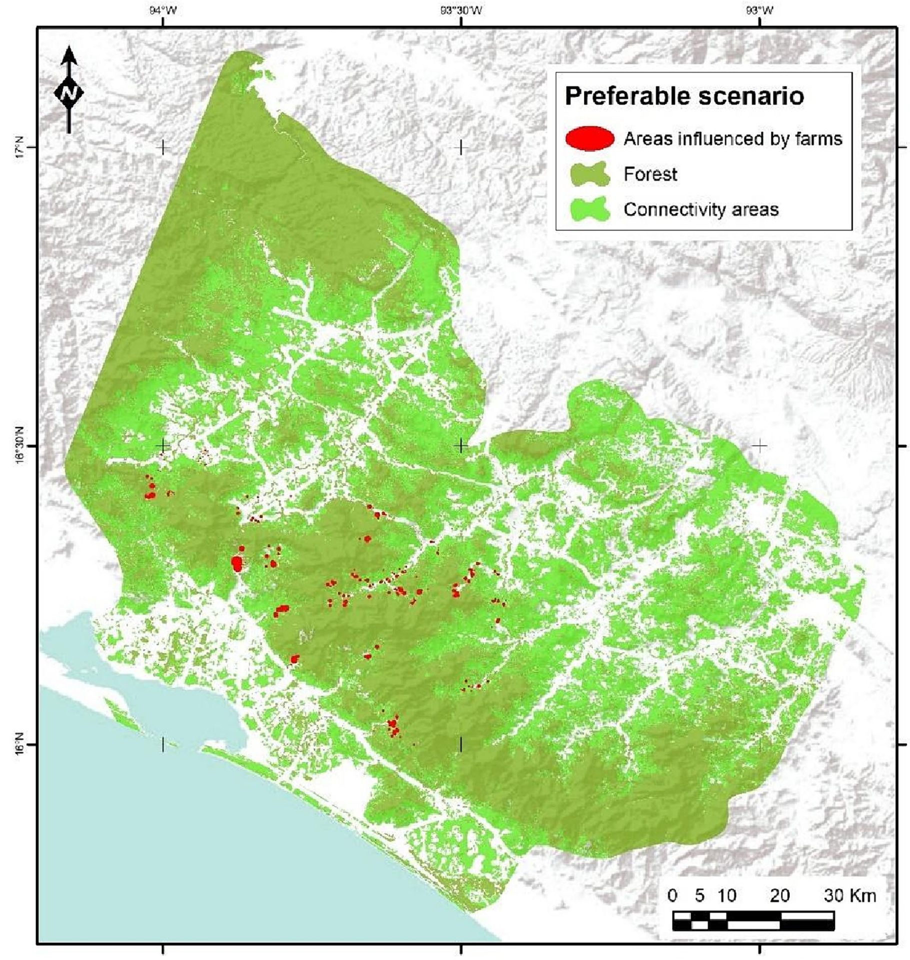

FIGURE 10
Preferable scenario for conservation: integrating medium, high, and very high suitability areas under AHP analysis.

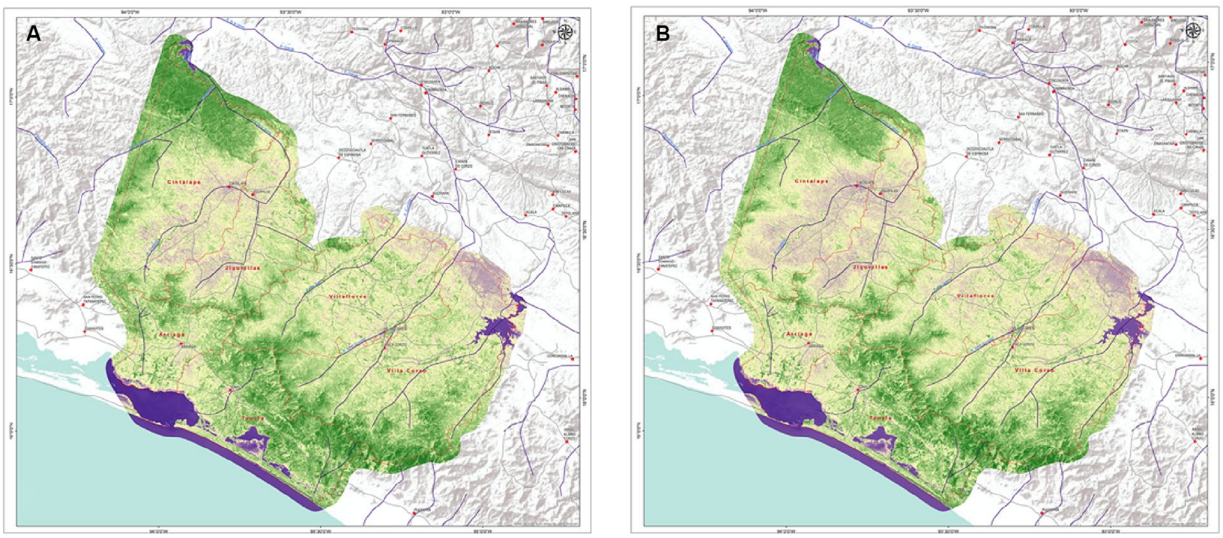

FIGURE 11
Temporal vegetation dynamics: comparing enhanced vegetation index (EVI) as proxy to vegetation vigor for **(A)** 2016; **(B)** 2021.

Hemeroby offers a holistic approach to assessing human impact on the landscape, integrating data on land use and the extent of human transformation. This is particularly valuable in landscapes where human activities have substantially altered the natural environment. Differing from indices solely based on landscape geometry, the hemeroby Index is ecologically sound and more straightforward to interpret regarding human influence on the landscape.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

LP-H: Conceptualization, Investigation, Supervision, Writing – original draft, Writing – review & editing, Methodology. CS: Funding acquisition, Resources, Visualization, Writing – review & editing. JJ: Project administration, Visualization, Writing – review & editing. JB: Visualization, Writing – review & editing. EP-S: Writing – review & editing. LN: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Software, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Akar, Ö., and Güngör, O. (2012). Classification of multispectral images using random Forest algorithm. *J. Geodesy Geoinform.* 1, 105–112. doi: 10.9733/jgg.241212.1

Alonso, A. J., and Lamata, T. M. (2006). Consistency in the analytic hierarchy process: a new approach. *Int. J. Uncertain. Fuzziness Knowledge-Based Syst.* 14, 445–459.

Azzari, G., and Lobell, D. (2017). Landsat-based classification in the cloud: An opportunity for a paradigm shifts in land cover monitoring. *Remote Sens. Environ.* 202, 64–74. doi: 10.1016/j.rse.2017.05.025

Baeza, S., Paruelo, J. M., and Altesor, A. (2006). Caracterización funcional de la vegetación del Uruguay mediante el uso de sensores remotos. *Interciencia* 31, 382–388.

Belgiu, M., and Dragut, L. (2016). Random forest in remote sensing: a review of applications and futuredirections. *ISPRS J. Photogramm. Remote Sens.* 114, 24–31. doi: 10.1016/j.isprsjprs.2016.01.011

CONABIO. (2020). Cobertura del suelo de México 30 metros. Comisión Nacional Para El Conocimiento y Uso de La Biodiversidad. Available at: http://www.conabio.gob.mx

Congalton, R. (1991). A review of assessing the accuracy of classifications of remotely sensed data. *Remote Sens. Environ.* 37, 35–46. doi: 10.1016/0034-4257(91)90048-B

Daszak, P., Das Neves, C., Amuasi, J. H. D., Kuiken, T., Roche, B., Zambrana-Torrelio, C. B. P., et al. (2020). IPBES Workshop on Biodiversity and Pandemics. *Execut. Sum.* doi: 10.5281/zenodo.4147317

Estrada-Carmona, N., Sanchez, A. C., Remans, R., and Jones, S. K. (2022). Complex agricultural landscapes host more biodiversity than simple ones: a global meta-analysis. *PNAS* 119, 1–10. doi: 10.1073/pnas

Fehrenbach, H., Grahl, B., Giegrich, J., and Busch, M. (2015). Hemeroby as an impact category indicator for the integration of land use into life cycle (impact) assessment. *Int. J. Life Cycle Assess.* 20, 1511–1527. doi: 10.1007/s11367-015-0955-y

Fischer, J., Abson, D. J., Butsic, V., Chappell, M. J., Ekroos, J., Hanspach, J., et al. (2014). Land sparing versus land sharing: moving forward. *Conserv. Lett.* 7, 149–157. doi: 10.1111/conl.12084

Fu, B. J., Hu, C. X., Chen, L. D., Honnay, O., and Gulinck, H. (2006). Evaluating change in agricultural landscape pattern between 1980 and 2000 in the loess hilly region of Ansai County, China. *Agric. Ecosyst. Environ.* 114, 387–396. doi: 10.1016/j.agee.2005.11.012

Fülöp, J. (2004). Introduction to decision making methods. *Workshop* 3, 1–15.

Gómez, M., and Barredo, J. (2006). *Sistemas de información geográfica y evaluación multicriterio en la ordenación del territorio*. Madrid, España: RA-MA.

Gorelick, N., Hancher, M., Dixon, M., Ilyushchenko, S., Thau, D., and Moore, R. (2017). Google earth engine: planetary-scale geospatial analysis for everyone. *Remote Sens. Environ.* 202, 18–27. doi: 10.1016/j.rse.2017.06.031

Harvey, C. A., Martínez-Rodríguez, M. R., Cárdenas, J. M., Avelino, J., Rapidel, B., Vignola, R., et al. (2017). The use of ecosystem-based adaptation practices by smallholder farmers in Central America. *Agric. Ecosyst. Environ.* 246, 279–290. doi: 10.1016/j.agee.2017.04.018

Harvey, C. A., Villanueva, C., Esquivel, H., Gómez, R., Ibrahim, M., Lopez, M., et al. (2011). Conservation value of dispersed tree cover threatened by pasture management. *For. Ecol. Manag.* 261, 1664–1674. doi: 10.1016/j.foreco.2010.11.004

INEGI. (2013). Continuo de Elevaciones Mexicano 3.0 (CEM 3.0). Mapas de Relieve Continental. Available at: https://www.inegi.org.mx

INEGI. (2019). Vías terrestres de Jalisco, Campeche y Chiapas. Infraestructura de Datos Espaciales de CentroGeo. Available at: https://biopasos.geoint.mx/

Jiménez, J. (2002). El proceso analítico jerárquico (AHP). Fundamentos, metodología y aplicaciones. *Rect@ Revista Electrónica de Comunicaciones y Trabajos de ASEPUMA* 1, 28–77.

Jiménez Trujillo, A. J., Díaz Ramírez, R., Niño Hernández, J. G., and Galdámez Moreno, D. (2020). *Caracterización de la ganadería bovina del Estado de Chiapas*. México. Documento de trabajo.

Jin, H., Stehman, S., and Mountrakis, G. (2014). Assessing the impact of training sample selection on accuracy of an urban classification: a case study in Denver, Colorado. *Int Journal of Remote Sensing* 26, 217–222. doi: 10.1080/01431161.2014.885152

Kumar, L., and Mutanga, O. (2018). Google earth engine applications since inception: usage, trends, and potential. *Remote Sens.* 10, 1–15. doi: 10.3390/rs10101509

Liu, C., Frazier, P., and Kumar, L. (2007). Comparative assessment of the measures of thematic classification accuracy. *Remote Sens. Environ.* 107, 606–616. doi: 10.1016/j.rse.2006.10.010

Malczewski, J. (2006). GIS-based multicriteria decision analysis: a survey of the literature. *Int. J. Geogr. Inf. Sci.* 20, 703–726. doi: 10.1080/13658810600661508

Mutanga, O., and Kumar, L. (2019). Google earth engine applications. *Remote Sens.* 11, 1–4. doi: 10.3390/rs11050591

NASA (2023). *Fire information for resource management system FIRMS* National Aeronautics and Space Administration NASA. MODIS Active Fire Data URL: firms.modaps.eosdis.nasa.gov

Neyret, M., Fischer, M., Allan, E., Hölzel, N., Klaus, V. H., Kleinebecker, T., et al. (2021). Assessing the impact of grassland management on landscape multifunctionality. *Ecosyst. Serv.* 52:101366. doi: 10.1016/j.ecoser.2021.101366

Niño, L. (2017). Zonificación minera basada en la integración de la evaluación ambiental estratégica y modelado con múltiples criterios en la región de La Macarena, departamento del Meta, Orinoquía Colombiana. *Revista Biollania* 15, 634–666.

Niño, L. (2019). "Aspectos cartográficos de la vegetación, los ecosistemas y las amenazas en la Serranía de Manacacías (Meta) Orinoquía colombiana" in *Colombia Diversidad Biótica Vol. XVII: La región de la Serranía de Manacacías (Meta) Orinoquía colombiana*. eds. J. O. Rangel-Ch, G. Andrade-C, C. Jarro-F and G. Santos-C (Bogotá, Colombia: Universidad Nacional de Colombia), 573–600.

Niño, L., Jaramillo, A., Villamizar, V., and Rangel, O. (2023). Geomorphology, land-use, and hemeroby of foothills in Colombian Orinoquia: classification and correlation at a regional scale. *Pap. Appl. Geogr.* 9, 295–314. doi: 10.1080/23754931.2023.2189921

Olofsson, P., Foody, G., Herold, M., Stehman, S., Woodcock, C., and Wulder, M. (2014). Good practices for estimating area and assessing accuracy of land change. *Remote Sens. Environ.* 148, 42–57. doi: 10.1016/j.rse.2014.02.015

Pal, M. (2005). Random forest classifier for remote sensing classification. *Int. J. Remote Sens.* 26, 217–222. doi: 10.1080/01431160412331269698

Perfecto, I., and Vandermeer, J. (2012). Separación o integración para la conservación de biodiversidad: la ideología detrás del debate "land-sharing" frente a "land-sparing." Available at: http://www.revistaecosistemas.net/articulo.asp?Id=715

Peterseil, J., Wrbka, T., Plutzar, C., Schmitzberger, I., Kiss, A., Szerencsits, E., et al. (2004). Evaluating the ecological sustainability of Austrian agricultural landscapes—the SINUS approach. *Land Use Policy* 21, 307–320. doi: 10.1016/j.landusepol.2003.10.011

Pezo, D., Muschler, R., Tobar, D., and Pulido, A. (2019). Intervenciones y tecnologías ambientalmente racionales (TAR) para la adaptación al cambio climático del sector agropecuario de América Latina y el Caribe.

Plourde, L., and Congalton, R. (2003). Sampling method and sample placement:how do they affect the accuracy ofRemotely sensed maps? *Photogramm. Eng. Remote Sens.* 69, 289–297. doi: 10.14358/PERS.69.3.289

Probst, P., Wright, M., and Boulesteix, A. (2019). Hyperparameters and tuning strategies for random forest. *WIREs Data Mining Knowledge Dis.* 9:e1301. doi: 10.1002/widm.1301

Raed, M., Gari, J., Berlles, J., Sedeño, A., Porta, P., Delise, L., et al. (1996). Métodos de clasificación supervisada y no supervisada de imágenes SAR ERS 1/2. *Proceedings of an Lnternational Seminar on the Use and Applications of ERS in Latin America*, (Viña del Mar, Chile: European Space Agency). 287–292.

Reiche, J., Lucas, R., Mitchell, A., Verbesselt, J., Hoekman, D., Haarpaintner, J., et al. (2016). Combining satellite data for better tropical forest monitoring. *Nat. Clim. Chang.* 6, 120–122. doi: 10.1038/nclimate2919

Rosenfield, G., and Fitzpatrick-Lins, K. (1986). A coefficient of agreement as ameasure of thematic classification accuracy. *Photogramm. Eng. Remote Sens.* 52, 223–227.

Saaty, T. (1994). How to make a decision: the analytic hierarchy process. *Interfaces* 24, 19–43. doi: 10.1287/inte.24.6.19

Saaty, T., and Shang, J. (2011). An innovative orders-of-magnitude approach to AHP-based mutli-criteria decision making: prioritizing divergent intangible humane acts. *Eur. J. Oper. Res.* 214, 703–715. doi: 10.1016/j.ejor.2011.05.019

Schneiders, A., and Müller, F. (2017). "A natural base for ecosystem services" in *Mapping ecosystem services*. eds. B. Burkhard and J. Maes (Sofia, Bulgaria: Pensoft Publishers), 33–38.

Serbin, S., and Townsend, P. (2020). "Scaling functional traits from leaves to canopies" in *Remote sensing of plant biodiversity*. eds. J. Cavender-Bares, J. Gamon and P. Townsend (Cham, Switzerland: Springer), 43–82.

Singh, A. (1987). Spectral separability of tropical forest cover classes. *Int. J. Remote Sens.* 8, 971–979. doi: 10.1080/01431168708954741

Steinhardt, U., Herzog, F., Lausch, A., Müller, E., and Lehmann, S. (1999). "Hemeroby index for landscape monitoring and evaluation" in *First international conference on environmental indices: Systems analysis approach*. eds. Y. Pykh, D. Hyatt and R. Lenz (EOLSS Publ: Oxford), 237–254.

Tobar-López, D., Bonin, M., Andrade, H. J., Pulido, A., and Ibrahim, M. (2019). Deforestation processes in the livestock territory of La Vía Láctea, Matagalpa, Nicaragua. *J. Land Use Sci.* 14, 225–241. doi: 10.1080/1747423X.2019.1671907

Tsai, Y., Stow, D., Chen, J., Lewison, R., An, L., and Shi, L. (2018). Mapping vegetation and land use types in Fanjingshan National Nature Reserve Using Google Earth Engine. *Remote Sens.* 10, 1–14. doi: 10.3390/rs10060927

Tscharntke, T., Klein, A. M., Kruess, A., Steffan-Dewenter, I., and Thies, C. (2005). Landscape perspectives on agricultural intensification and biodiversity - ecosystem service management. *Ecol. Letters* 8, 857–874. doi: 10.1111/j.1461-0248.2005.00782.x

Walz, U., and Stein, C. (2009). Indicators of hemeroby for the monitoring of landscapes in Germany. *J. Nat. Conserv.* 22, 279–289. doi: 10.1016/j.jnc.2014.01.007

Waske, B., and Braun, M. (2009). Classifier ensembles for land cover mapping using multitemporal SAR imagery. *ISPRS J. Photogramm. Remote Sens.* 64, 450–457. doi: 10.1016/j.isprsjprs.2009.01.003

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Changes in the economics of coffee production between 2008 and 2019: a tale of two Central American countries

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Increasing costs of coffee production relative to coffee prices has led to concern across the industry of lack of profitability of coffee production especially for smallholders who comprise a large majority of producers. This study compares coffee production costs and income over a decadal interval of 2008 versus 2019 for coffee farmers in some of the main coffee growing regions of Costa Rica and Guatemala. Costs and income were collected by farmer recall using a standard questionnaire with trained research surveyors. Net income as assessed by EBITDA (earnings before interest, taxes, depreciation and amortization) increased by about 30% in Costa Rica, but declined to a third of its 2008 level in Guatemala. Agronomic costs of production per hectare increased by 31% in Costa Rica and 62% in Guatemala, mostly due to increased labor costs (higher daily wage rates), while fertilizer usage increased but unit costs remained stable. Gross income was stable in Guatemala but increased in Costa Rica due to receiving significantly higher prices for their coffee in 2019 compared to 2008, while in Guatemala prices declined. Nevertheless, the response was not uniform between farms in Costa Rica while high and medium productivity groupings of farms had higher EBITDA, low and very low productivity farms experienced a decline similar to Guatemala. The difference in performance of farm groups in Costa Rica was due to a decline in production per hectare of the lower productivity group; while the difference between Guatemala and Costa Rica was firstly due to price differences, and secondarily due to lower productivity of some farm groups. The investment of Costa Rican farmers was undoubtedly supported by the substantially increased price received by farmers (as compared to Guatemala), reflected in the increase in export price of coffee from Costa Rica relative to Guatemala. This shows the importance of farmers receiving higher prices for their produce in enabling them to cover increasing production costs, invest in increasing productivity and maintain profitability.

KEYWORDS

agronomic costs, coffee prices, Guatemala, Costa Rica, EBITDA, productivity

1 Introduction

Coffee production is estimated to provide livelihoods for between 12.5 to 25 million farmers and their families (Enveritas, 2019; ICO, 2019), of which about 95% are smallholders with farms less than 5 hectares (Enveritas, 2019). Although global coffee production has increased by 65% since 1990, prices continue to be highly volatile. Since the end of the International Coffee Agreement and market liberalization at the beginning of the 1990s coffee prices crashed in the early 2000s recovered toward the end of that decade and then again between 2009 and 2019 declined by 30% (ICO2019). In 2018 prices dropped below US$1.00 per pound for the first time since the price crash of the early 2000s. Coffee producers were struggling to cover their operating costs during the period of 2016–2019, due to rising input, compliance and transaction costs (ICO, 2019). Even for the 2015/16 harvest, before prices declined further, between 25 and 50% of farmers across Colombia, Honduras and Guatemala were experiencing negative profits, being unable to cover their full economic costs of production. Rising costs and falling prices have resulted in up to half of coffee producing smallholders living below the extreme poverty line in some countries (ICO 2020). While coffee prices have recovered somewhat over the 2020–2022 period, price volatility is inherent and systemic in coffee production, with farmers facing prices below production costs a few years in every decade.

Over longer time frames (1970–2019) there is no significant trend of prices increasing nor decreasing (ICO, 2019), but costs of production have increased sharply since 2010 thus reducing profits for producers (Sachs et al., 2019). Cordes et al. (2021) found that average coffee income was below a living income for all top ten coffee producing countries except Brazil. The main drivers of poor economic performance appeared to vary between countries, while in Colombia and Guatemala high production costs were important (and in general for Latin America), in Uganda low farmgate prices and small farm size, and Ethiopia low coffee productivity were key factors.

Central America is one of the main coffee growing regions of the world producing approximately 10% of global production but specializing in high quality arabica coffees supporting about 290,000 farmers and is a major source of income and employment in rural areas (CEPAL, 2002). Guatemala is the eighth largest coffee producer globally and fourth largest producer of Arabica coffee. Both Guatemala and Costa Rica have a reputation for producing very high quality and specialty coffees. The countries share some macro variables that make the comparative analysis relevant, such as inflation rates, tax burden, being in the same region, and open market economies. Moreover, both countries are exposed to changes in commodity and input prices and are dependent on importing fertilizers and other inputs and exporting their production. Agroclimatic conditions for production are similar in the two countries and coffee production systems are similar derived from traditional shaded agroforestry systems with varying degrees of intensification, but not high input, irrigated monocultures as in Vietnam or parts of Brazil. Nevertheless, socioeconomic conditions in the two countries are distinct with Guatemala having one of the highest poverty and inequality rates in Latin America (The World Bank, 2024a), the highest poverty level in Central America while Costa Rica has higher levels of overall income, a relatively equitable distribution of wealth and high levels of education and social welfare (The World Bank, 2024b). Thus, the two countries have similar conditions for coffee production but within distinct economic and social conditions.

Since the dissolution of the International Coffee Agreement in 1989 that buffered price fluctuations, there have been price crashes between 1991–1993, 2000–2003 (Bacon, 2008), and substantial fluctuations subsequently. The fall in coffee prices between 2000 and 2003 led to a 25% reduction in coffee production across Central America and the loss of half a million jobs (Castro et al., 2004). Addressing the financial instability among coffee producers remains an on-going challenge with many different industry and development programs attempting to address the issue. There are various initiatives between industry and development organizations seeking to determine what is a living income for coffee farmers such as the IDH (2020) Task Force for a Living Income report, while Fairtrade International (https://www.fairtrade.net/issue/living-income) have established a Living Income Reference Price for some countries. Most recently the International Coffee Organization with United Nations Industrial Development Organization launched a report on the sustainability and resilience of global coffee value chains and proposed the establishment of a Global Coffee Fund address the financial instability of the sector (ICO and UNIDO, 2024).

Changes in costs of production summarized by Sachs et al. (2019) indicate considerable differences between countries, perhaps due to different levels of investment in labor compared to inputs. Is it stated that both increases in labor costs and inputs costs were drivers of reduced profitability. It might be expected that higher wage economies such as Costa Rica would be at a disadvantage to lower wage economies such as Guatemala. Nevertheless, clear data on changes in production costs over time appear to be lacking. Overall, past studies lack comparable data at farm level across time to ascertain the main causes and responses to the perceived decline in profitability of coffee production in countries whose primary producers are smallholders.

In this study we aim to determine the changes in the on-farm economics of coffee production over a decadal period between 2008 and 2019 under the distinct socioeconomic conditions of Guatemala and Costa Rica to understand the factors that may be contributing to falling profitability or enabling farmers to maintain their incomes.

2 Methods and data

2.1 Methods

The study applied the Committee for Sustainability Assessment (COSA) method for multi-criteria assessment of sustainability in coffee (Giovannucci and Potts, 2008) to characterize farms and evaluate coffee production costs and income from coffee on farms across Guatemala and Costa Rica. This is a method that can be implemented in between half to one day per farm; while this limits the depth of evaluation it also permits larger sample sizes to be undertaken.

Two surveys were undertaken, one in 2008/09, the other in 2019/20. The 2008/09 survey was conducted across all the main coffee growing regions in each country, was structured to compare farms with sustainability certification and those without and included a total of 237 farms in Costa Rica and 273 farms in Guatemala (Soto et al., 2011). Certified farms were selected from lists provided by certification bodies and traders in-country, and non-certified farms were identified from the same communities with similar characteristics.

The 2019/20 survey selected farms from the 2008/09 data-base but focused on three of the main coffee growing regions in each country covering a range of agro-environmental conditions, as described in Haggar et al. (2021). In Costa Rica, farms were located in: (i) Turrialba-Orosi (low-medium altitude, high rainfall, standard commercial grade coffee); (ii) Valle Occidental (mid-high altitude, seasonal climate with high quality coffee), and (iii) Los Santos Tarrazú (high altitude, seasonal climate, and coffee quality that is considered the best in the country). In Guatemala, farms were located in: West (departments of Quetzaltenango, Retalhuleu, and San Marcos) low-high altitude, high rainfall, commercial grade coffee; Mid (department of Solola) high altitude, medium rainfall, high quality coffee; and East (departments of Guatemala, Sacatepequez and Chimaltenango) high altitude, low rainfall, and very high coffee quality. A total of 180 farms (90 per country, 30 per region) were initially selected from a list used in a previous study in 2008/09. Where these farms were not available or interested in participating they were replaced by nearby farms of similar characteristics (56 in total). Ethical standards of prior consent and confidentiality were followed as appropriate for socioeconomic surveys and farmers were at complete liberty to decline to participate (as a few did).

Two surveyors experienced in farm verification processes conducted the farmer questionnaires, but different surveyors were used for the two evaluation periods. Surveyors received training, conducted trial interviews, and interview responses were reviewed periodically to ensure quality with feedback provided. All variables were quality checked in order to identify values out of acceptable or standardized ranges. All the values identified as outliers were reviewed or corrected with the producer in a second visit or phone call.

In both surveys we used the COSA questionnaires to register all coffee agronomic practices and estimate the costs of those practices during the previous year, (2008 and 2019) as well as the amount of coffee produced, harvest costs and value of sales for the harvest prior to and after the period evaluated for its agronomic costs (i.e., 2007/08 and 2008/09, and 2018/19 and 2019/20 harvests). The actual timing of the survey varied as the agronomic year and start and end of harvest varied across the different regions with some completing harvest in November and others until April. The COSA format is designed to facilitate the reconstruction of costs from farmer recall by working through the practices for the farming year; this is supported by the registers of activities and use of records farmers are required to maintain when they are certified, but are less common for non-certified farmers.

To make the monetary values of both surveys comparable, the values from the 2008/09 survey were multiplied by 1.1874, which reflects the change in the composite Consumer Price Index between 2008 and 2019. Moreover, for each survey the data for production and price was averaged between two adjoining harvests given the known tendency for biennial production, i.e., a good year is generally followed by a poorer year in terms of production per hectare. This avoids excessive fluctuations. The averages are from the 2007/08 and 2008/09, and 2018/19 and 2019/20 harvests, which are referred to 2008 and 2019 for simplicity. Price and production of cherry coffee was used for all farms. When a farm sold coffee in another presentation, standard conversions were used to transform back to cherry.

2.2 Data analysis

To study a coffee farm's profits in a given year consider that

$$\Pi = TI - TC, \quad (1)$$

where Π is profits per hectare, TI is total income per hectare and TC is total costs per hectare. In this study EBIDTA (earnings before interest, taxes, depreciation and amortization) is used as a proxy for profits. Expressing the equation with a normalization by plantation size facilitates comparability between farms, and allows for a simple conversion to totals profits, income and cost by multiplying by area. Moreover, consider that

$$TI = PQ, \quad (2)$$

where P is the average price and Q the average production sold per hectare for the harvest for which the production costs were evaluated, and the previous harvest. Costs can be analyzed in different ways to obtain a better picture of underlying dynamics. An initial and relatively simple way is to decompose costs among input costs and labor costs, with

$$TC = IC + LC, \quad (3)$$

where IC are input costs per hectare and LC are labor costs per hectare. For input costs, the materials (e.g., fertilizer, pesticides, etc.) and equipment (e.g., machetes, tractors, etc.) for all practices were registered noting the volume or number of the product and the cost per unit. For labor costs, the number of person-days and cost per day were registered for all activities. All person-days were considered as a cost, regardless if they generated a monetary payment or if they were family work. Another way to decompose costs is between activities, with

$$TC = \sum AgC + HC + FC, \quad (4)$$

where $\bullet$ AgC contains the costs per hectare of all agronomic activities (i.e., establishment, pruning, manual weed control, conservation, shade management, fertilization, and pesticides), HC are harvesting costs per hectare, and FC are fixed costs per hectare. These costs contain input and labor costs, with all person-days considered as a cost as specified above. Costs of labor for the harvest and processing were calculated (including picking, wet processing, and drying) based on a cost per volume of harvest (as this is how these services are usually paid). The amount and price of materials, tools and equipment used in harvest and processing were registered; in the case of minor equipment that lasts more than a year, total cost was divided by life-span as an estimate. Additional costs were registered including, fuel used (for machinery), transport costs, and administration costs. Fixed costs such as equipment depreciation, maintenance and administrative costs were considered yet played a relatively small part in overall costs. Farms where costs were incomplete or substantially deviated from the normal range of values were eliminated from the analysis.

Based on the 2019 dataset a coffee plantation typology of production strategies was formed for each country using multivariate cluster analysis based on the shade LAI and coffee yield as indicators of sustainability and productivity outcomes of the management strategy of the plantation (Haggar et al., 2021). Cluster analysis of plantations per country was conducted using LAI and coffee productivity ($kg\,ha^{-1}$), previously standardized, using the Ward method with Euclidean distance. The resulting clusters represent the coffee plantation production strategies that reflects the strategy in terms of intensification and sustainability. Four production strategies were differentiated for each country representing high, medium, low and very low productivity plantations, with varying shade levels (Appendix Table A1). Production strategies significantly differed in the levels of agronomic investment, coffee yield, and shade levels, amongst other factors (Haggar et al., 2021), and can be summarized as follows.

High Productivity Medium Shade (HPMS), were high yielding plantations producing between 12 and 20 tonnes of coffee cherries per hectare annually, with high investment in agronomic production over US$2000 per hectare. Most plantations had between 40 and 60% shade (LAI 0.5–1.1).

Medium Productivity Low/Medium Shade (MPLS/MS) plantations produced between 6 and 12 tonnes (Costa Rica) and 4–12 tonnes (Guatemala) of coffee cherries per hectare per year. Annual agronomic costs in Costa Rica were almost as high as Hprod-Mshade systems, but only about US$1,100 per hectare in Guatemala. Shade levels in both countries were 20–60% (LAI 0.1–1.0), although on average higher in Guatemala.

Low Productivity High Shade (LPHS) was characterized by having high shade over 60% (LAI > 1.0), while productivity ranged from <1 tonne to 9 tonnes of coffee cherries per hectare per year. Annual agronomic costs were on average half that of the Medium Productivity systems, US$1277 per hectare in Costa Rica and US$689 per hectare in Guatemala.

Very Low Productivity Low/Medium Shade (VLPLS/MS) systems had annual yields from <1 tonne up to 6 tonnes of coffee cherries per hectare and shade levels less than 60% (LAI <1.0), although on average higher for Guatemala. Agronomic production costs were very similar to that for the LPHS system.

Differences in EBITDA between 2008 and 2019 by country were made using t-tests. The subset of data that only includes farms for which there is data for both dates were compared using paired t-tests. Paired t-tests were also used to compare the differences in the components of economic costs and income between 2008 and 2019. ANOVA with Tukey means comparison was used to compare the EBITDA in 2019 of farm typology groupings, and the change in EBITDA 2008–2019 for each group.

Moreover, to further study the determinants of EBITDA a regression analysis is made on EBITDA per hectare, production per hectare, price, and unit costs. OLS with robust standard errors are used to regress each of these variables on altitude, farm area, producer age, certification of coffee (dummy), participation in a producer association (dummy), and survey year (dummy).

3 Results

3.1 Change in EBIDTA across sampling groups

The absolute value of EBIDTA from coffee production in 2019 and 2008, and the differences between them were very similar whether calculated using all data from the two surveys, only from farms in the same regions, or only farms in common between the two surveys (Table 1). In Costa Rica the comparison of farms in 2008 and 2019 using all data gave a weakly significant increase in EBIDTA which might have been influenced by the 2008 data covering a wider geographic area than the 2019 data. The values for farms in the same regions and farms in common gave similar absolute values but the slight increase in EBIDTA was no longer significant. In Guatemala all comparisons showed a highly significant decline in EBIDTA with income in 2019 only 30% of that in 2008 (Table 1). For further exploration of the factors that contribute to this difference we have used the comparison between the same farms to ensure changes between the time periods are not influenced by differences between the farms included. This limits the sample size to 69 farms for Costa Rica for each year, and 38 for Guatemala.

3.2 Drivers of changes in EBITDA

In 2008 the mean EBITDA from coffee producers in Guatemala was 180% that of Costa Rica, but by 2019 it had fallen to only 40%. This change is due to a large and statistically significant drop in EBITDA in Guatemala (i.e., a drop of 75%) compared to a small and

TABLE 1 EBIDTA - earnings before interest, taxes, depreciation and amortization - (USD per hectare) from coffee production averaged for all farms surveyed in each country in each year, those farms found in the regions in common between the two survey years, and those farms in common between the two surveys.

	Costa Rica			Guatemala		
Variables	All data	Common regions	Common farms	All data	Common regions	Common farms
EBITDA 2019	1,356.5 (2,003.3)	1,356.5 (2,003.3)	1,412.9 (1,961.9)	499.4 (1,431.2)	499.4 (1,431.2)	560.0 (1,481.8)
N in 2019	82	82	69	75	75	38
EBITDA 2008	1,020.3 (1,368.3)	1,082.6 (1,511.0)	1,259.5 (1,756.2)	1,660.8 (1,427.8)	1,697.2 (1,444.5)	2,276.3 (1,445.2)
N in 2008	224	168	69	247	121	38
Difference	336.2* (201.7)	273.9 (227.4)	153.4 (317.0)	−1,162.5*** (188.3)	−1,197.8*** (211.5)	−1,716.3*** (335.8)
Total *N*	306	250	138	322	196	76

Standard deviation in parenthesis. For the difference it is the standard error in parenthesis. Difference in EBITDA is obtained from running a *t*-test on both samples.
***, **,* Refers to 1, 5, and 10% significance level of *t* test for difference of means.

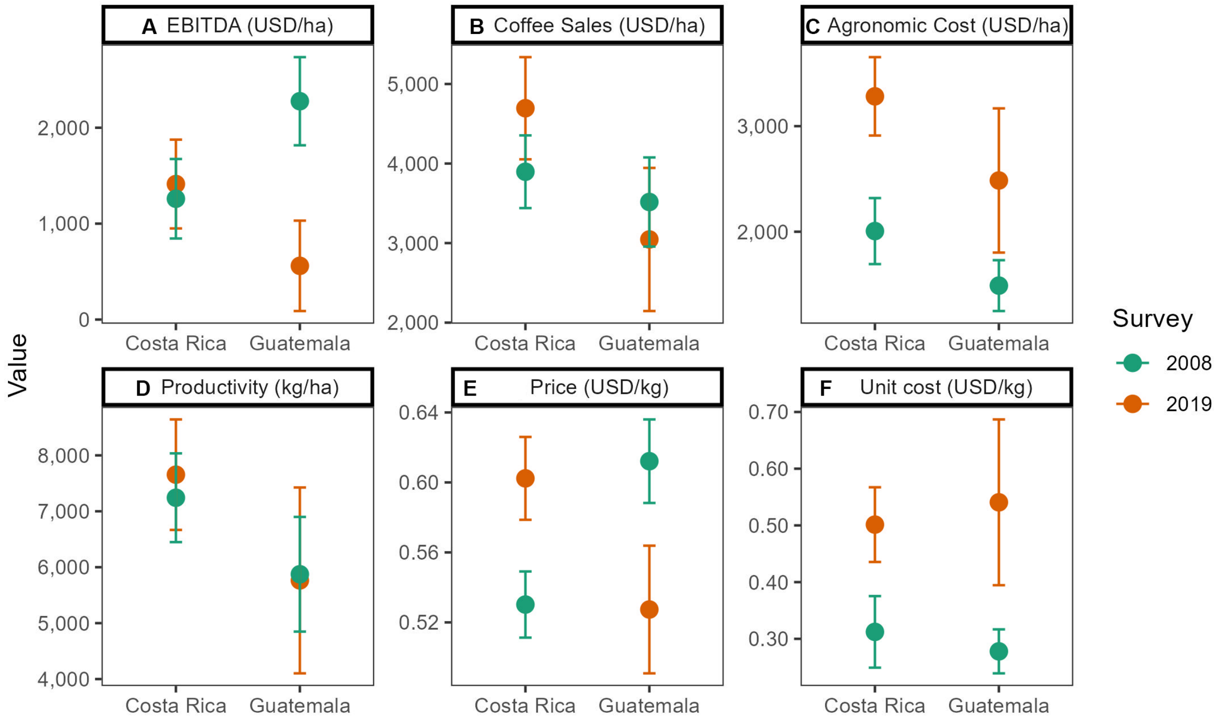

FIGURE 1
EBITDA, coffee sales, agronomic costs, production per hectare, price and unit cost for Costa Rica and Guatemala in 2008 and 2019 (same farms; error bars represent 95% confidence intervals).

non-statistically significant increase of EBITDA in Costa Rica (Figure 1A).

The contrasting dynamic of EBITDA seems to come from coffee sales falling in Guatemala and rising in Costa Rica, despite the changes being not statistically significant (Figure 1B). Costs rose in both countries by similar amounts in absolute and relative terms, which were statistically significant (Figure 1C). In Guatemala agronomic costs increased by USD 995 and 66% while in Costa Rica the increase was of USD 1276 and 64%.

Although not significantly, gross income from coffee sales rose in Costa Rica but fell in Guatemala due to changes in coffee prices (Figure 1E), while productivity remained unchanged in both countries. Guatemala experienced a statistically significant drop in price of 13.8%, while Costa Rica had a statistically significant increase of 13.6%. Thus, while in 2008 Guatemala farmers obtained $0.082/kg of coffee cherries more than Costa Rican farmers (15.4% difference), by 2019 this had inverted with Costa Rican farmers receiving $0.075/kg of coffee cherries more than Guatemala (14.2% difference). Both agronomic costs per ha and unit costs per kg of coffee increased in both countries with statistical significance and by similar amounts (Figures 1C,F). What is different between countries is that Guatemala also experienced an increase in variability of unit and agronomic costs suggesting differing responses among farmers in the country. A deeper understanding of this variability can be found exploring the main components of the total agronomic cost per hectare as presented in Figure 2.

Mean input costs increased in both countries with statistical significance, yet rose considerably more in Guatemala (158%) than Costa Rica (35%) (Figure 2A). Moreover, the variability in Guatemala increased sharply, indicating that the increased investment in inputs was not uniform across farms. On the other hand, mean labor costs increased significantly only in Costa Rica by 76%, while variability increased in both countries (Figure 2B). This suggests that the increase in agronomic cost in Costa Rica was driven by labor costs, while Guatemala's increase in levels and variability was mostly driven by input costs.

Further insights can be found exploring the components of the total cost per hectare as presented in Figure 3.

Statistically significant increases in mean costs are found for both countries in the establishment of new plantations, the use of fertilization, and the use of pesticides. These increases in means are accompanied by a notable increase in variability, especially in Guatemala. In the case of fertilization in Guatemala, the increase in variability makes the increase statistically significant only at the 10% level of significance. Establishment costs increased by 1,516% in Guatemala and 669% in Costa Rica, fertilizer cost by 123% in Guatemala and 40% in Costa Rica, and pesticide costs by 4,126% in Guatemala and 196% in Costa Rica. Harvest cost also increased, albeit with lower statistical significance, by 53% in Guatemala and 24% in Costa Rica. This may in part be due to a larger percentage increase in production per hectare in Guatemala than Costa Rica, although overall production costs per hectare was higher in Costa Rica than Guatemala (Figure 1D). Lastly, in Costa Rica there was a notable increase in manual weed control costs, which while not statistically significant explains the larger increase in labor costs in Costa Rica (Figure 3C).

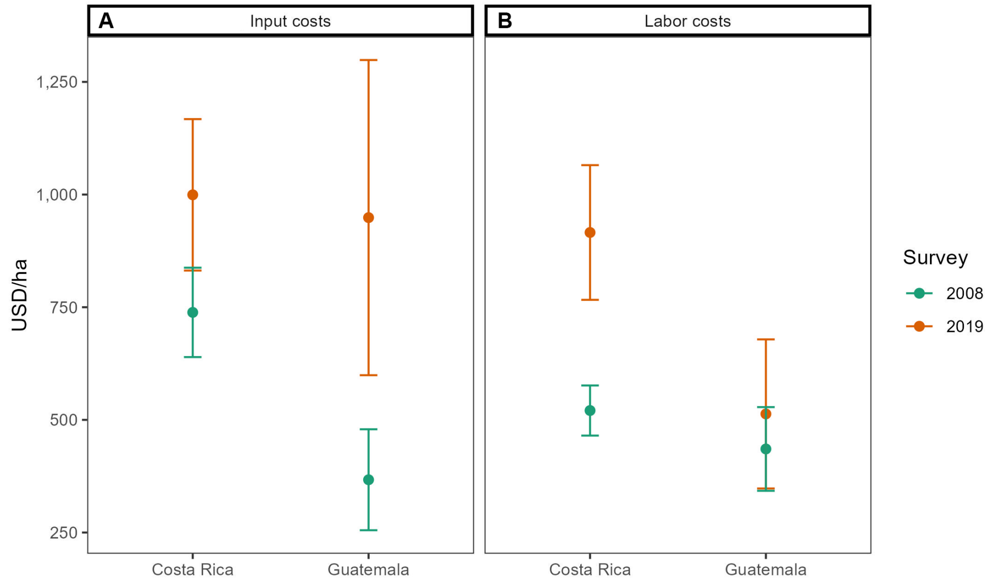

FIGURE 2
Input and labor costs per hectare for Costa Rica and Guatemala in 2008 and 2019 (same farms; error bars represent 95% confidence intervals).

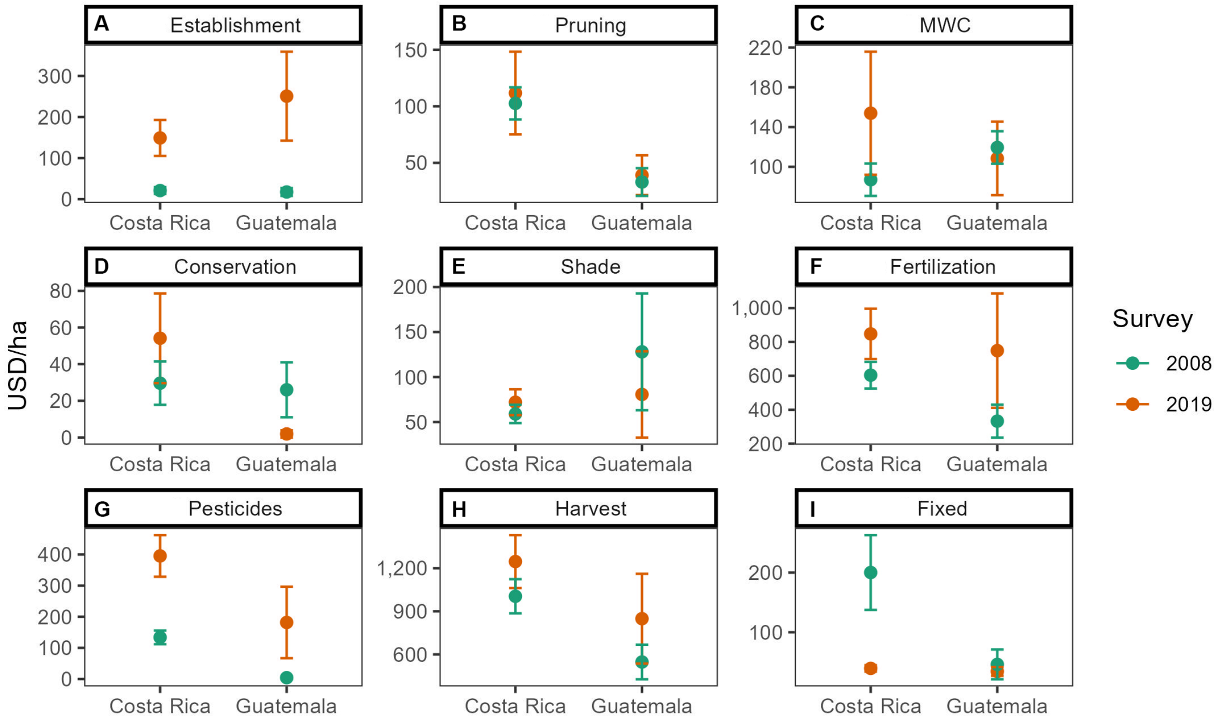

FIGURE 3
Decomposition of total cost per hectare for Costa Rica and Guatemala in 2008 and 2019 (same farms; error bars represent 95% confidence intervals).

3.3 Farm characteristics associated with differences in EBITDA

Multiple regression models showed the same differences between survey years in production per hectare, unit cost of production, price, and resulting EBITDA as indicated above (Table 2). Production per hectare was significantly and positively associated with altitude in both countries and with certification in Guatemala but was negatively associated with farmers being part of an association in Guatemala (Table 2A). Coffee price was positively associated with altitude and farm size in Costa Rica, and with certification in Guatemala (Table 2B). Costs of production of a kilogram of coffee were negatively associated with altitude in Costa.

TABLE 2 Influence of farm characteristics on (A) EBITDA and coffee productivity, and (B) coffee price and unit costs of production based on all farms in regions present in both surveys.

(A)				
	EBITDA (USD/ha)		Productivity (kg/ha)	
Variables	Costa Rica	Guatemala	Costa Rica	Guatemala
Certification (1 = Yes)	246.6	511.0**	544.4	1,220**
	(237.7)	(231.3)	(507.0)	(527.9)
Farm area (ha)	2.270***	0.130	1.984*	−2.255
	(0.566)	(0.491)	(1.064)	(2.181)
Altitude (m)	2.435***	0.0663	6.372***	0.863**
	(0.419)	(0.222)	(0.774)	(0.418)
Association (1 = Yes)	215.0	−478.2*	154.6	−1,605**
	(251.1)	(246.5)	(475.7)	(628.5)
Producer age	−3.683	3.546	3.751	10.59
	(8.025)	(8.383)	(17.17)	(21.53)
Survey (1 = 2019)	408.5*	−1,034***	675.9	933.5
	(224.4)	(228.0)	(483.0)	(615.3)
Constant	−2,138***	1,366***	−1,780	3,150**
	(697.3)	(499.0)	(1,339)	(1,329)
Observations	249	184	249	184
R-squared	0.205	0.174	0.256	0.075

(B)				
	Price (USD/kg)		Unit cost (USD/kg)	
Variables	Costa Rica	Guatemala	Costa Rica	Guatemala
Certification (1 = Yes)	0.0334	0.0450***	−0.0629	−0.181
	(0.0270)	(0.0150)	(0.0905)	(0.151)
Farm area (ha)	0.000183***	0.000109*	−0.000379	−0.000188
	(4.05e-05)	(6.43e-05)	(0.000262)	(0.000149)
Altitude (m)	8.61e-05**	−3.07e-06	−0.000363**	−7.59e-05
	(3.86e-05)	(1.35e-05)	(0.000149)	(0.000128)
Association (1 = Yes)	0.0309	0.00834	0.0444	0.115
	(0.0309)	(0.0147)	(0.0516)	(0.171)
Producer age	0.000291	−0.000578	0.00136	−0.00959
	(0.000415)	(0.000472)	(0.00171)	(0.00908)
Survey (1 = 2019)	0.101***	−0.0574***	0.0748	0.422**
	(0.0163)	(0.0139)	(0.0814)	(0.171)
Constant	0.351***	0.579***	0.818***	1.000
	(0.0656)	(0.0359)	(0.234)	(0.640)
Observations	249	184	249	184
R-squared	0.172	0.245	0.047	0.075

Values are mean effects of farm characteristics with standard errors in parenthesis.

These effects combined led to higher altitude and larger farm size significantly and positively affecting EBIDTA in Costa Rica, and certification significantly and positively affecting EBIDTA in Guatemala. There was a weakly significant negative effect of association on EBIDTA in Guatemala which is likely an effect of the low production per hectare of associated farmers, but it is not

TABLE 3 Economic performance of coffee farms by typology grouping for (A) all farms in 2019 and (B) change between 2008 and 2019 for those farms in both surveys.

	Costa Rica				Guatemala			
Typology	HPMS	MPLS	LPHS	VLPLS	HPMS	MPMS	LPHS	VLPMS
(A) 2019								
EBITDA USD/ha	3,564 a (1,528)	2,126 b (1,527)	1,257 b (1,479)	−485 c (1,340)	1,968 a (2,128)	1,047 ab (1,194)	142 bc (1,198)	−337 c (860)
Productivity kg/ha	12,883 ab (2,490)	9,947 b (2,428)	5,470 c (2,870)	3,660 c (1,603)	14,868 a (4,691)	7,006 b (2,850)	3,291 c (2,154)	1,764 c (1,259)
Price USD/kg	0.61 ab (0.06)	0.63 ab (0.07)	0.69 a (0.36)	0.52 b (0.11)	0.47 a (0.11)	0.55 a (0.08)	0.51 a (0.13)	0.49 a (0.07)
Unit cost USD/kg	0.34 a (0.07)	0.43 a (0.12)	0.50 a b (0.22)	0.68 b (0.40)	0.33 ab (0.11)	0.41 a (0.18)	0.62 a b (0.52)	1.70 b (2.81)
Number of farms	13	22	23	24	8	26	23	18
(B) Difference between 2008 and 2019								
EBITDA USD/ha	2,028 a (1,270)	982 a b (2,466)	−507 b c (1,892)	−1,268 c (1,778)	−372 a (1,735)	−1,694 a (1,671)	−1834 a (1,833)	−2,459 a (2,547)
Productivity kg/ha	3,170 a (2,879)	1,859 a (3,354)	−1,147 b (2,986)	−1,315 b (2,560)	9,738 a (4,856)	267 b (2,827)	−2,167 b (4,228)	−3,329 b (2,790)
Price USD/kg	0.07 ab (0.05)	0.10 a (0.06)	0.10 a (0.12)	0.01 b (0.11)	−0.10 a (0.11)	−0.02 a (0.07)	−0.11 a (0.18)	−0.12 a (0.15)
Unit cost USD/kg	0.01 a (0.13)	0.10 a (0.41)	0.24 a (0.24)	0.34 a (0.53)	0.07 a (0.15)	0.18 a (0.30)	0.33 a (0.63)	0.41 a (0.52)
Number of farms	11	19	21	18	5	15	11	7

Typology codes are HPMS, high productivity medium shade; MPLS/MS, medium productivity low or medium shade; LPHS, low productivity high shade; VLPLS/MS, very low productivity low or medium shade. More details are available in methods. Values that share the same letter are not significantly different at the 5% level of significance.

possible to determine whether this is because low productivity farmers tend to be members of associations, or being a member of an association somehow leads to lower productivity. It should be noted that in many cases to be certified farmers need to be members of an association (and there is a certain correlation between the two rho = 0.33), but that the variance associated with certification has been allocated as a separate variable.

3.4 Changes in EBIDTA and economics of production for different farm typology groups

The EBIDTA of farms in different typology groups representing different production strategies were significantly different in both countries (Table 3A), and thus indicate that the responses described above were not uniform across all farm types. High productivity Medium Shade had the highest EBIDTA in both countries although not statistically different from Medium Productivity Medium Shade in Guatemala. Low Productivity High Shade EBIDTA was not statistically different from Medium Productivity Medium/Low Shade in both countries, but was significantly higher than Very Low Productivity Low Shade in Costa Rica. Differences in EBIDTA between typology groups were closely related to productivity (as productivity was the main factor the groups were based upon). The price received for coffee was similar across typology groups except for Very Low Productivity Low Shade in Costa Rica which received a significantly lower price than Low Productivity High Shade. Unit costs of producing a kilogram of coffee were significantly higher for very low productivity groups in both countries compared to high and medium productivity groups.

Changes in EBIDTA between 2008 and 2019 were only positive for High and Medium productivity farms in Costa Rica (Table 3B). The other typology groups in Costa Rica and all Guatemalan groups in Guatemala had reduced EBIDTA between these two dates. There were no statistically significant differences between typology groups in Guatemala probably due to the small sample size for paired farms. The changes in EBIDTA were again partially related to changes in productivity with high and medium productivity groups in both countries experiencing increases in productivity compared to declines for Low and very low productivity groups (although not statistically significant for medium productivity from those with reduced productivity in Guatemala). All groups in Costa Rica except the very low productivity group had significant increases in price received for coffee, while all the groups in Guatemala experienced declines in price received.

4 Discussion

As claimed by other studies (e.g., ICO, 2019; Sachs et al., 2019) agronomic costs of production per hectare have increased by about

30–60% due to both increases in labor and input costs in both countries, even when costs are dollarized and adjusted for inflation. However, these differences integrate both increased unit costs and increased investment in production. The daily rate for labor increased by 31% (from US$ 5.2 to 6.8/day) in Guatemala and 71% in Costa Rica (from US$ 9.3 to 15.9/day). While the cost of the main fertilizers used decreased by 10–22% in Guatemala and 11–29% in Costa Rica, with very similar costs in the two countries [it should be noted that there was a sharp rise in fertilizer prices in 2008 prior to the economic crash (Hedebrand and Laborde, 2022)]. The decrease in unit costs of fertilizer but increase in total fertilizer costs indicates that in both countries farmers increased the rate of fertilization. Although production per hectare on average remained the same in both countries there was high and medium productivity farms increased their productivity while on low and very low productivity farms productivity declined. This may represent two different responses by farmers to increasing costs, one to reduce investment in production and the other to increase investment, especially in fertilizer, to boost production and thus increase income. Analysis by Lalani et al. (2023) found that the high productivity group was the most profitable across a range of input and labor cost scenarios.

Both countries were investing considerably more in establishment of coffee plantations in 2019 than 2008, possibly due to impacts of the coffee rust outbreak in 2013. Furthermore, Guatemalan farms are investing relatively more than their Costa Rican counterparts. This indicates that Guatemalan farms have a larger area of new as yet unproductive coffee, which would reduce farm-level production per hectare of coffee plantation. As this probably only affects a proportion of farms it probably also contributes to the high variability in cost per kilogram produced due to the additional costs from establishment of new plantings being included in some cases.

The positive economic impact of Costa Rican farmers intensifying production appears to contradict conclusions from the systematic review of Jezeer et al. (2017) that lower intensity production systems were more profitable. The economic performance of the production strategies from the typology were analyzed by Lalani et al. (2023) demonstrating that high input but also moderately shaded coffee generated the highest net, but if there was a 50% fall in coffee prices then high input production had the greatest losses. In contrast low-input highly shaded coffee had lower returns under the labor and input cost variations tested but generated the lowest losses if coffee prices crashed. It needs to be assessed whether the higher use of fertilizer by Costa Rican farmers can be sustained with the doubling of fertilizer costs that occurred in 2022 (Hedebrand & Laborde, 2022), which was greater than the 50% increase modeled by Lalani et al. (2023).

Other factors that appear to support reducing production costs and increasing EBIDTA are higher altitude and larger farm size (both in Costa Rica), and certification in Guatemala. Haggar et al. (2017) also found in Nicaragua that farmers under some certifications achieved a greater EBIDTA than their matched peers. Unfortunately, altitude and farm size are not factors farmers can easily change, and certification requires investment and close alliance with private traders or trading farmer cooperatives. Nevertheless, Wollni and Zeller (2007) found that farmers in Costa Rica do benefit from price differentials associated with specialty markets and that cooperative association was an important means for them to access those markets.

In terms of impact on EBIDTA, the differences in prices received by farmers in Costa Rica and Guatemala probably has the greatest impact. In 2008 farmers in Guatemala reported farm gate prices 10% higher than in Costa Rica, but by 2019 this had substantially reversed. The 2008 differences in the farm gate prices are similar to those reported on the ICO website (https://www.ico.org/new_historical.asp accessed August 2022), with prices of USD 1.11 vs. USD 1.06 per lb. green coffee in Guatemala and Costa Rica, respectively (note our prices are quoted as USD per kg of coffee cherries), and thus not a sampling effect. Unfortunately no comparable data are available for 2019. Estimates of average export prices taken from the United Nations COMTRADE database (https://comtrade.un.org/data/, accessed July 2022) indicate that the average coffee export prices for Guatemala and Costa Rica were USD 2.81 versus USD 3.07 per kilo green coffee in 2008, and USD 3.09 versus USD 4.38 per kilo green coffee in 2019. It should be noted that these prices have not been adjusted for inflation, unlike the prices shown in Figure 3, if a similar adjustment is made to these prices it would also show a lower inflation-adjusted price in 2019 of USD 2.06 for Guatemala yet still a higher one of USD 3.69 for Costa Rica in agreement with the data used in this study. Thus the farm-gate prices reported to us by farmers correspond to and are likely a result of differences in export prices. The USDA Global Agricultural Information Network annual reports indicate similar export prices for 2019 of USD 3.33–3.66 per kilo for Guatemala and USD 4.35 per kilo for Costa Rica (https://www.fas.usda.gov/data/costa-rica-coffee-annual-6, https://www.fas.usda.gov/data/guatemala-coffee-annual-5); this against world market prices for "other milds" as reported by ICO (https://www.ico.org/new_historical.asp accessed August 2022) for 2008 and 2019 of USD 3.07 and USD 2.87 per kilo green coffee. Thus, both countries had managed to improve export prices compared to market trends, though Costa Rica managed to increase its export price differential substantially more during this period.

Nevertheless, production and export of coffee in Costa Rica has declined (from over 2.2 million sacks in early 2000s, to 1.8 million 2011/2012 to just over 1.4 million sacks 2018/19), while in Guatemala it has more or less been maintained fluctuating between 3.2 and 4.0 million sacks between 2000 and 2019 (https://www.ico.org/new_historical.asp accessed August 2022). Indeed in 2018/19 Guatemala maintained production of about 3.7 million sacks, while Costa Rican production was below average compared to the previous decade. This may have increased prices internally in Costa Rica as exporters competed for coffee to meet their contracts with buyers. The Specialty Coffee Transaction Guide: 2022 (www.transactionguide.coffee) developed by researchers from Emory University summarizes contract values for specialty coffee between 2019 and 2022 calculated a median price for Costa Rica of USD 3.65 per pound compared to USD 3.00 for Guatemala, this despite Guatemala having a slightly higher median quality score. It has been noted that Costa Rican producers have invested in many micro-mills to process and sell high quality micro-lots at substantially higher prices, but also maintaining a reputation for environmental and social standards as well as product quality (USDA, 2022). Thus, Costa Rican farmers and their organizations have taken the next step from simply accessing markets that provide specialty prices (as reported by Wollni and Zeller, 2007) to now adding further value through micro-processing for direct sales to specialist roasters. As Jacobi et al. (2024) found in Colombia and Bolivia, direct sales of coffee to international buyers or even local markets provide the greatest economic benefits to farmers.

5 Conclusion

Without doubt increased production costs, and above all labor costs have affected the economics of coffee production in the two countries studied. However, it is notable that while labor costs in Costa Rica are about double that in Guatemala, Costa Rican farmers have been able to maintain their profitability better than Guatemalan farmers. In part this seems to be due to some groups of Costa Rican farmers having achieved higher productivity through higher investment, indeed only high and medium productivity farms had increased EBITDA. However, this investment has been substantially supported by increases in prices received by most Costa Rican farmers, while prices received in Guatemala declined. Indeed, high productivity Guatemalan farmers who invested in increasing productivity did not benefit economically due to the lower price they received for their coffee. Higher prices in Costa Rica have been supported by a reduction in the volume of coffee offered by Costa Rica, but also by higher social and environmental standards, and increases in direct sales and sales of processed coffee. This demonstrates the role of buyers and consumers paying prices that appropriately compensate the costs of production and provide a living income to farmers. Ultimately the higher prices received by Costa Rican farmers is probably what has enabled them to maintain or even increase coffee productivity while paying substantially higher wages compared to other countries in the region such as Guatemala.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Ethics statement

Ethics procedures of the University of Greenwich and the Centro Agronómico Tropical de Investigación y Enseñanza were followed, ensuring prior informed consent of all participants.

Author contributions

BL: Formal analysis, Investigation, Methodology, Writing – original draft, Writing – review & editing. FC: Data curation, Formal analysis, Investigation, Methodology, Supervision, Writing – review & editing. AV: Data curation, Formal analysis, Investigation, Writing – review & editing. JH: Conceptualization, Funding acquisition, Methodology, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Bacon, C. (2008). "Confronting the coffee crisis: can fair trade, organic and specialty coffees reduce the vulnerability of small-scale farmers in northern Nicaragua?" in Confronting the coffee crisis: Fair trade, sustainable livelihoods and ecosystems in Mexico and Central America. eds. C. M. Bacon, V. E. Mendez, S. R. Gliessman and J. A. Fox (Cambridge, MA: MIT), 155–178.

Castro, F., Montes, E., and Raine, M. (2004). "La crisis cafetalera: Efectos y estrategias para hacerle frente" in Sustainable development working paper 23 (The World Bank: Washington).

CEPAL (2002). Centroamérica: El impacto de la caída de los precios de café en 2001. Chile: Comisión Económica para América Latina y el Caribe.

Cordes, KY, Sagan, M, and Kennedy, S. (2021). "Responsible coffee sourcing: towards a living income for producers," Columbia Center on Sustainable Investment. Available at: https://scholarship.law.columbia.edu/cgi/viewcontent.cgi?article=1198&context=sustainable_investment_staffpubs

Enveritas. (2019). How many coffee farmers are there? Global coffee farm study. Available at: https://carto.com/blog/enveritas-coffee-poverty-visualization/ (Accessed June 16, 2023).

Giovannucci, D., and Potts, J. (2008). Seeking sustainability: COSA preliminary analysis of sustainability initiatives in the coffee sector. Winnipeg, Canada: IISD, 37.

Haggar, J., Casanoves, F., Cerda, R., Cerretelli, S., Gonzalez, S., Lanza, G., et al. (2021). Shade and agronomic intensification in coffee agroforestry systems: trade-off or synergy? *Front. Sustain. Food Syst.* 5:645958. doi: 10.3389/fsufs.2021.645958

Haggar, J., Soto, G., Casanoves, F., and de Melo, V. E. (2017). Environmental-economic trade-offs and benefits of sustainably certified coffee farms. *Ecol. Indic.* 79, 330–337. doi: 10.1016/j.ecolind.2017.04.023

Hedebrand, C, and Laborde, D (2022). High fertilizer prices contribute to rising global food security concerns. Available at: https://www.ifpri.org/blog/high-fertilizer-prices-contribute-rising-global-food-security-concerns (Accessed June 16, 2023).

ICO. (2019). Coffee development report 2019: growing for prosperity – economic viability as the catalyst for a sustainable coffee sector. Available at: https://www.internationalcoffeecouncil.org/eng/coffee-development-report.php

ICO and UNIDO. (2024) Sustainability and resilience of the coffee global value chain: towards a coffee investment vehicle. Available at: https://www.unido.org/news/unido-and-ico-publish-report-sustainability-resilience-coffee-global-value-chain-towards-global-investment-vehicle (Accessed June 21, 2024).

IDH. (2020) Task force for coffee living income. Available at: https://www.idhsustainabletrade.com/publication/task-force-for-coffee-living-income-report-summary (Accessed June 21, 2024).

Jacobi, J., Lara, D., Opitz, S., de Castelberg, S., Urioste, S., Irazoque, A., et al. (2024). Making specialty coffee and coffee-cherry value chains work for family farmers' livelihoods: a participatory action research approach. *World Dev. Perspect.* 33:100551. doi: 10.1016/j.wdp.2023.100551

Jezeer, R. E., Verweij, P. A., Santos, M. J., and Boot, R. G. A. (2017). Shaded coffee and cocoa – double dividend for biodiversity and small-scale farmers. *Ecol. Econ.* 140, 136–145. doi: 10.1016/j.ecolecon.2017.04.019

Lalani, B., Lanza, G., Leiva, B., Mercado, L., and Haggar, J. (2023). Shade versus intensification: trade-off or synergy for profitability in coffee agroforestry systems? *Agric. Syst.* 214:103814. doi: 10.1016/j.agsy.2023.103814

Sachs, J, Cordes, KY, Rising, J, Toledano, P, and Maennling, N. (2019). Ensuring economic viability and sustainability of coffee production. Columbia Center Sustain. Invest. doi: 10.2139/ssrn.3660936

Soto, G., Haggar, J, Le Coq, JF, Gonzalez, C, Soto, A, Casanoves, F, et al., (2011). Environmental and socioeconomic impact of organic coffee certification in Central America as compared with other certification seals. Pp. 120–123 in eds D Neuhoff, S Mok Sohn, C Ssekyewa, N Halberg, I Rasmussen and J Hermansen, Organic is Life - Knowledge for Tomorrow. Volume 1 - Organic Crop Production. Proceedings of the Third Scientific Conference of the International Society of Organic Agriculture Research (ISOFAR)

The World Bank. (2024a). The World Bank in Guatemala: overview. Available at: https://www.worldbank.org/en/country/guatemala/overview

The World Bank. (2024b). The World Bank in Costa Rica: overview. Available at: https://www.worldbank.org/en/country/costarica/overview

USDA. (2022). Costa Rica: coffee annual. Report Number CS2022-CS0008. Available at: https://fas.usda.gov/data/costa-rica-coffee-annual-6

Wollni, M., and Zeller, M. (2007). Do farmers benefit from participating in specialty markets and cooperatives? The case of coffee marketing in Costa Rica. *Agric. Econ.* 37, 243–248. doi: 10.1111/j.1574-0862.2007.00270.x

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Appendix

TABLE A1 Coffee production strategy according to productivity and shade level as assessed by LAI (Leaf Area Index) (N = number of farms in the group) [adapted from Haggar et al. (2021)].

Costa Rica					Guatemala				
Production Strategy	N	Yield (kg ha^{-1})	LAI	Agronomic cost US$ ha^{-1}	Production Strategy	N	Yield (kg ha^{-1})	LAI	Agronomic cost US$ ha^{-1}
High productivity Medium shade (HPMS)	14	13,750 a	0.80 b	2,117 a	High productivity Medium shade (HPMS)	8	16,298 a	0.54 b	2,471 a
Medium productivity Low shade (MPLS)	24	9,436 b	0.41 c	2012 a	Medium productivity Medium shade (MPMS)	26	6,990 b	0.66 b	1,137 a
Low Productivity High shade (LPHS)	26	5,361 c	1.46 a	1,277 b	Low-Productivity High shade (LPHS)	34	2,879 c	1.71 a	689 b
Very low production Low shade (VLPLS)	25	3,132 d	0.47 c	1,377 b	Very low production Medium shade (VLPMS)	22	1,699 d	0.63 b	625 b

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Climate-smart agriculture reduces capital-based livelihoods vulnerability: evidence from Latin America

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Introduction: Climate change poses a significant threat to rural livelihoods in low- and middle-income countries. Enhancing the sustainability of these livelihoods is crucial for ensuring food security and nutrition at both global and regional levels. This study investigates the role of Climate Smart Agriculture (CSA) practices in improving rural livelihoods in Latin America, specifically through the Climate Smart Village (CSV) approach.

Methods: Our analysis involved a dataset of 267 households, comprising both adopters and non-adopters of CSA practices in CSVs across Guatemala, Honduras, and Colombia. We employed multiple correspondence analysis (MCA), Gower's metric, agglomerative clustering, partitioning around medoids (PAM), and cluster validation. Our aim was to understand how CSA practices, which include the use of agroclimatic information, soil and water management practices, and risk diversification strategies, contribute to enhancing livelihoods. We examined this in the context of the five capitals (social, natural, physical, financial, and human) of the Sustainable Livelihoods Framework (SLF).

Results: Our findings indicate that CSA farmers exhibit lower capital-based vulnerability compared to non-CSA farmers. This is particularly evident in the areas of social capital, as well as human and natural capital for certain CSA adopters. However, the similar performance in financial and physical capital between CSA and non-CSA farmers suggests the need for additional strategies to reduce vulnerability in these areas. We examined this through the Sustainable Livelihoods Framework (SLF), which includes five capitals: social, natural, physical, financial and human.

Conclusion: These findings offer a valuable framework for policy and decision-making processes, helping to identify which capitals and dimensions of livelihood vulnerability should be prioritized in different contexts to achieve climate resilience and sustainable development. The study advocates for continued research efforts, incorporating expanded indicators, such as gender indicators within social and human capital definitions, for a more comprehensive assessment of CSA's impact. The application of SLF for analyzing CSA's contribution to rural livelihoods represents a novel approach in Latin American studies.

KEYWORDS

sustainable livelihoods framework, climate smart agriculture, climate-smart villages, social capital, natural capital, physical capital, financial capital, human capital

1 Introduction

Rural livelihoods dependent on agriculture face unprecedented challenges due to the growing impact of climate change on agricultural systems, particularly in low- and middle-income countries. Agriculture engages 14% of the total labor force and 55% of the rural labor force in the Latin America and Caribbean (LAC) region. Women make up 7.5% of the agricultural labor force of the region, including 41% of rural workers. The implications of climate change for the region are profound (IICA, 2019). Simultaneously, the sector itself contributes substantially to global emissions, underscoring the urgent need for sustainable practices.

While smallholder farmers, particularly women, are pivotal in global food production, their vulnerability to environmental shifts cannot be understated (Doss, 2018; Ricciardi et al., 2018; Donatti et al., 2019). Therefore, the pursuit of sustainable livelihoods for these communities is critical not only for regional food security but also for global sustainability. Building on the concept of sustainability, which involves the ability to withstand shocks and maintain resources for future generations, the Climate-Smart Agriculture (CSA) approach presents a holistic development strategy. CSA strives to enhance the resilience and productivity of agricultural systems, ensure food security, and mitigate environmental pressures and greenhouse gas emissions.

Despite the growing body of literature on CSA and its role in enhancing agricultural resilience and productivity, a comprehensive exploration that integrates the Sustainable Livelihoods Framework (SLF) within the context of CSA remains an untapped area of research. By emphasizing the interplay between natural, physical, social, human, and financial capitals, the SLF provides a comprehensive lens to assess the impact of CSA on rural livelihoods.

This study aims to fill this gap by examining how CSA contributes to the sustainability of rural livelihoods in Latin America and the Caribbean, leveraging secondary field data from three distinct geographies. The paper not only adds to the existing evidence on the effectiveness of CSA at scale in reducing the vulnerability of agriculture-dependent households but also highlights the importance of adopting a dual framework approach bringing the SLF and the CSA approaches together for robust policy recommendations and investments. Furthermore, the study provides a unique comparative analysis of the implementation of the Climate-Smart Village (CSV) approach across different geographic locations, providing insights into the varying impacts of CSA practices on rural livelihoods. By exploring the changes in the diverse livelihood capitals resulting from the adoption of CSA practices, this study provides a nuanced understanding of the interconnected dynamics between climate-resilient agriculture and sustainable livelihoods in the face of a changing climate landscape.

2 Climate-smart agriculture (CSA) and the sustainable livelihoods framework (SLF)

The impacts of climate change have placed significant strains on rural communities, leading to resource degradation, food shortages, and social inequalities (Gentle and Maraseni, 2012; Gitz et al., 2016; Ray et al., 2019). These challenges have disrupted the delicate equilibrium of agriculture-based livelihoods, highlighting the vulnerability of rural communities to climate change (Lal et al., 2011; Singh et al., 2021). Extensive research on climate variability and change in agriculture has unequivocally underscored the importance of climate-smart agriculture (CSA) as a crucial strategy to mitigate the adverse impacts of climate change on both food security and livelihoods, as emphasized by Manda et al. (2016). CSA refers to agricultural practices that aim to enhance productivity, resilience, and sustainability in the face of climate change challenges by integrating climate adaptation and mitigation strategies (Lipper et al., 2014). CSA aims to secure food production while minimizing environmental impacts and strengthening the resilience of farming communities.

Lipper and Zilberman (2018) explore the evolution and key features of the CSA concept. Initially, the CSA concept aimed at meeting three main objectives: sustainably increasing food security, building resilience to climate change, and reducing greenhouse gas emissions. However, challenges arose due to the lack of a clear methodology, resulting in varied interpretations and controversy. Over time, a methodology emerged, emphasizing the need for evidence-based assessments, an enabling policy environment, and coordinated investments. The Climate Smart Agriculture sourcebook, released in 2013, defined CSA practices, highlighting resource use efficiency and resilience enhancement (FAO, 2013). Further refinement of the CSA methodology occurred through a consultative process, addressing controversies and emphasizing the broader spatial and temporal scales of CSA objectives. Recent developments include "country CSA profiles," providing critical evaluations of ongoing practices, institutional support, and a methodology for assessing climate-smart agriculture at the country level. A key CSA goal is to improve rural livelihoods so that they are resilient to external shocks such as climate change. Such resilience can be assessed through different dimensions embedded in livelihoods. The sustainable livelihoods framework has well-described the different assets or capitals embraced by livelihoods.

The sustainable livelihood capital approach is a conceptual framework used in the field of sustainable development and poverty reduction. Numerous authors in the development community have developed and evolved the approach through research and practice (Habib et al., 2023). It is used to understand and analyze the resources and assets that people and communities have at their disposal to improve their living conditions. The five main capitals considered in this approach are human, social, financial, physical, and natural; however, some authors have proposed adding more capitals to the approach. The analysis of how people and communities take advantage, strengthen, and generate synergies between these capitals helps to understand and generate the enabling conditions to improve the adaptation of each person or community to the specific conditions that surround them (Yin et al., 2020).

The CSA and sustainable livelihoods frameworks are complementary approaches for understanding and promoting adoption of practices to increase resilience to climate change. However, scientific literature that integrates both approaches is still limited. We found eight articles that analyzed CSA in relation to the concept of sustainable livelihoods or the SLF (Table 1). None of those had a focus in Latin America. This is the first study analyzing CSA contribution in the light of the SLF in Latin America.

3 Materials and methods

The methodology employed in this study comprises three primary stages. Initially, we focused on data processing and variable selection, involving the identification of crucial variables for each livelihood capital, consolidation of mixed variables, and thorough cleansing of databases, including addressing missing data, outliers, and ensuring a single observation per household. Subsequently, we undertook farm-type characterization using a combination of multiple correspondence analysis and cluster analysis. This step included the careful selection of the most appropriate clustering method to analyze both continuous and discrete variables, employing the multiple correspondence method, and ultimately generating distinct clusters. Finally, we formulated the Livelihood Vulnerability Index (LVI) by assessing the comprehensive vulnerability of the studied livelihoods.

3.1 Study area

The study was conducted in three Climate Smart Villages (CSV) in Latin-American: Cauca, Colombia; Olopa, Guatemala; and Santa Rita, Honduras. Despite their distinct agro-climatic and geographical features, these villages exhibit similar farm socioeconomics, climate vulnerability, and adaptation strategies. The study used 2020 household survey data (Bonilla-Findji et al., 2020a,b,c). In brief, the CSV farming households are characterized by smallholder rainfed crop farming systems of staple crops, fruit trees and small livestock, with mostly a small-to-marginal farm size (Table 2). Furthermore, farming households from the three CSVs show similar adaptation strategies to climate change implemented through the climate smart village (CSV) approach framework of the Climate Change, Agriculture and Food Security (CCAFS) program (López et al., 2020). The analogous nature of the catalogues of CSA practices adopted by these three CSVs allows us to compare the impact of CSA adoption on capital-based livelihood vulnerability, which is the main focus of the paper, by combining regional data from three different locations.

3.2 Data used

The data used in the study corresponds to three published datasets containing household survey information from the "Integrated

TABLE 1 Collection of articles that analyzed CSA and sustainable livelihoods concept or framework.

	Approach	Aim	Geographic focus	Ref.
1	CSA	Explore climate-smart agriculture as a resilience-building tool to ensure sustainable agricultural practices to enhance sustainable livelihoods.	South Africa	Mathews et al. (2018)
2	CSA	Evaluate project effects on farmers livelihoods through the implementation of CSA	Kenya	Fuchs et al. (2019)
3	CSA	Understand the synergies and trade-offs of selected climate smart agriculture practices	Kenya	Ogola and Ouko (2021)
4	CSA	Understand the sensitivity of sorghum crop to various stress events due to climate change	N/A	Chadalavada et al. (2021)
5	SLF combined with value chain approach	Assess the values and the contribution of frankincense to household economies	Ethiopia	Berhanu et al. (2021)
6	CSA	Evaluate the role of climate-smart agriculture towards sustainable livelihoods	Zimbabwe	Muzorewa and Chitakira (2022)
7	CSA	Explore the synergies and trade-offs of climate-smart agriculture practices selected by smallholder farmers	Ethiopia	Tilahun et al. (2023)
8	SLF	Assess the livelihood status and delineate livelihood assets determining climatic vulnerability of farm households and promotes CSA.	India	Das et al. (2023)

TABLE 2 Distribution of farm sizes for households studied across the three Latin-American Climate-Smart Villages.

Latin-American CSVs	Number of households (%)	Farm size* (%)	Women respondents (%)
Cauca, Colombia	71 (26.6)	Large farms (2.8), Medium farms (31.0), Small farms (42.3), Marginal farms (23.9)	22.5
Olopa, Guatemala	89 (33.3)	Large farms (0.0), Medium farms (1.1), Small farms (4.5), Marginal farms (94.4)	48.3
Santa Rita, Honduras	107 (40.1)	Large farms (6.5), Medium farms (16.8), Small farms (23.4), Marginal farms (53.3)	20.6
Total	267	Large farms (3.4), Medium farms (15.4), Small farms (22.1), Marginal farms (59.2)	30.3

*Large farms (>4 ha), medium farms (2–4 ha), small farms (1–2 ha), and marginal farms (up to 1 ha). Source: Datasets (Bonilla-Findji et al., 2020a,b,c).

Monitoring Framework for Climate-Smart Agriculture" from the CCAFS research project (Bonilla-Findji et al., 2020a,b,c). The "Integrated Monitoring Framework for Climate-Smart Agriculture" was developed and used by CCAFS annually across the global network of Climate-Smart Villages to gather field-based evidence by tracking the progress on (i) adoption of CSA practices and technologies, as well as access to climate information services and (ii) their related impacts at household level (Bonilla-Findji et al., 2021).

The main objectives of the CSA monitoring framework are to (1) understand enabler and barriers for adoption of CSA technologies and practices; (2) understand gender-disaggregated perceived effects of CSA adoption, dis-adoption, control over resources and labour; and (3) understand CSA performance, synergies and trade-offs at the farm level. This framework introduces standardized descriptive indicators aimed at monitoring changes across various dimensions. These include five enabling dimensions that could influence adoption patterns, a core set of six indicators at the household level designed to evaluate the perceived impacts of CSA practices on aspects such as food Security, productivity, income, and climate vulnerability. Additionally, it incorporates four core indicators focusing on gender aspects, encompassing participation in decision-making, participation in implementation, access/control over resources, and work time. At the farm level, the framework includes seven core indicators to assess CSA performance, while also examining synergies and trade-offs among its three key pillars (Bonilla-Findji et al., 2021).

The final selection of monitoring household survey datasets from three Latin American countries were composed of 6 modules: (1) household demographics, (2) household agricultural activities, (3) exposure to climatic events, (4) access to weather and climatic information, (5) household food security and (6) adoption of CSA practices. From these modules within the CSV datasets, we selected the relevant information to construct the dataset for this study.[1] The CSA practices analyzed are listed in Table 3, it is important to note that according to the concept of CSA, practices and technologies should be implemented as portfolios considering context-specificities and acknowledging that sets of practices could actually contribute to climate smartness.

3.3 Data processing and variable selection

After selecting the final datasets, we proceeded with data processing by identifying the questions of the survey which addressed an aspect of a livelihood capital, from which a set of 23 unique mixed variables were constructed (Table 3). Each variable, whether numeric or categorical, represented one relevant aspect of a livelihood capital. All 23 variables were constructed based on previously used capital-based livelihood vulnerability indicators (Hahn et al., 2009; Pandey and Jha, 2012; Xu et al., 2020; Zhang et al., 2020; Zhang and Fang, 2020). We also consulted experts about factors that are known to influence capital-based livelihood vulnerability in Latin-American CSV farming households. The variable selection process resulted in a total of 23 mixed variables available for cluster analysis and farm type characterization. It is important to note that the survey dataset used covered relevant aspects of physical, financial, social and human capital extensively, whereas aspects of natural capital (such as soil or water quality) were less covered. For that reason, the natural capital variables selected represent qualitative proxies to estimate the state of natural resources in the farming household system.

Secondly, household records which contained no information on one or more of the selected survey questions were removed. Only households which had answered all the selected questions used to construct the 23 variables were included in the study. When there was more than one record per household, the answer from the head of household (man or woman) was prioritized and selected over the answers of other members of the household to ensure higher data reliability Despite the importance of assessing gender aspects in this study, the lack of systematic recording of two survey responses from both male and female head of household (especially in Cauca and Santa Rita CSVs) did not allow to include two responses per household and disaggregate the data by gender prior clustering. Finally, as a prerequisite for clustering, data quality checks were performed, which included removal of missing and out-of-range data, which unfortunately reduced the number of household records to use in the analysis, thus data did not allow enough reliability for performing gender analysis. Quantitative data were checked for outliers, which were removed to minimize bias and improve clustering. The average area destined for productive agricultural activities per household was restricted to a minimum of 200 m^2 and a maximum of 84,000 m^2 per household. Farming households which had a value outside that range were removed. No household had more than 10 combined number of tree species, crop species and livestock species.

TABLE 3 List of implemented CSA practices at each Latin American CSV.

Cauca, Colombia[1]	Olopa, Guatemala[2]	Santa Rita, Honduras[3]
Organic fertilizers	Organic fertilizers	Organic fertilizers
Water reservoirs	Water reservoirs	Water reservoirs
Rainwater harvesting	Rainwater harvesting	Rainwater harvesting
Drought-resistant biofortified seeds	Drought-resistant biofortified seeds	Drought-resistant biofortified seeds
Horticulture + rainwater harvesting	Horticulture + rainwater harvesting	Horticulture + rainwater harvesting
Windbreaks	Windbreaks	Agroforestry (Kuxur Rum)
Crop residue addition / Mulching	Living barriers	Living barriers
Irrigation	Terracing	Terracing
Camandula water pump	Aquaculture	Aquaculture
	Horticulture + Plastic cover	Shade management (Coffee)
	Conservation tillage	
	Contour trenches	

[1]2018 – CSA Monitoring – Cauca Climate Smart-Village Colombia (Bonilla-Findji et al., 2019).
[2] Martínez-Salgado and López (2020). Memories of CSV Olopa, Guatemala 2019.
[3] Martínez-Salgado and Alvarez (2020). Memories of CSV Santa Rita, Honduras 2019.

1 Further information on the surveys implemented as part of the monitoring framework can be found in Martínez-Salgado and López (2020); as well as Martínez-Salgado and Alvarez (2020); information available only for Guatemala and Honduras CSVs.

Variable selection, data selection and data quality checks were carried out using Microsoft Excel (2020) software. The data cleaning process trimmed the initial datasets to a total of 267 households to be used in this study—71, 89 and 107 household records from Cauca, Olopa and Santa Rita, respectively. Unfortunately, due to the total number of female responses being rather low (30.3%), a separation of the total household sample by gender was not considered, as the sub-sample of women responses (81) was too low for the statistical analysis.

3.4 Farm-type characterization with multiple correspondence and cluster analysis

The statistical analysis of the data was divided into four steps: (1) multiple correspondence analysis (MCA); (2) computing the dissimilarity between observations using Gower's metric; (3) agglomerative clustering using Ward's minimum variance method and partitioning around medoids (PAM), and; (4) cluster validation using the silhouette width method. All the analyses were conducted in R version 3.6.3 (R Core Team, 2020), using the R packages "cluster," "rtsne," "ggplot," "factoextra" and "factominer" for computing the clustering algorithms and respective visualizations. Table 4 shows the variables used in the cluster analysis.

First, to study the associations between the variables to be used in the cluster analysis, multiple correspondence analysis (MCA) was performed. MCA applies a dimensionality reduction algorithm to illustrate the principal components of the analysis in two dimensions. These two dimensions represent the combination of most influential variables in the analysis (Supplementary material). MCA allowed us to visualize the contributions of different variables to the combined first and second dimensions of the analysis, and therefore to identify the variables that most strongly influenced the variance of our data.

As a first step in the clustering Gower's metric was used to compute the distance or dissimilarity between each pair of observations, since this distance metric is suitable for mixed data types and the datasets contained both categorical and numeric variables (Martin, 2016; Kassambara, 2017). As a prerequisite for clustering, Gower's metric automatically normalized the data by rescaling it to a range between 0 and 1. Ward's minimum variance method was used as the agglomeration or linkage method to compute the minimum distance between clusters. Ward's method minimizes the total within-cluster variance, so that at each step of the clustering, the pair of clusters with minimum between-cluster distance are merged. Other authors also recommend using Gower's metric and Ward's linkage method for clustering mixed data (Chávez Esponda et al., 2010; Hendrickson, 2014; Martin, 2016). Once the distance information was obtained, agglomerative clustering was performed to obtain a tree-based representation of the objects (dendrogram). In agglomerative clustering, the cluster algorithm treats each single observation as a single cluster and pairs it with the next most similar cluster. This step is repeated until all clusters have been merged into one big cluster containing all objects, obtaining a dendrogram as a result (Kassambara, 2017).

After applying the clustering algorithm and computing the cluster distance information, the optimum number of clusters (k) that best represented the data was identified using the average silhouette method. This method allowed identifying the optimal number of clusters (k) which maximizes the average silhouette over a range of possible values for k (Kassambara, 2017). Once the number of optimum clusters (k) was selected, PAM partitioning (partitioning around the medoids) was performed, which partitions the data based on the most central point of each cluster (medoid). In k-medoids clustering, each cluster is represented by one of the data points in the cluster, the medoids, which correspond to the most centrally located point in each cluster. The medoids are therefore a representative example of the members of that cluster. As opposed to other types of clustering, the k-medoids statistical method is less sensitive to noise and outliers and it is compatible with the Gower distance metric (Martin, 2016). After PAM partitioning was performed, descriptive statistics of each cluster were obtained for interpretation and comparison of clusters. The above-mentioned steps for cluster analysis were performed first for all 267 CSV households. The same cluster analysis was then performed only for the 223 CSA farms which had adopted at least one CSA practice, in order to identify if implementation of at least one CSA practice has some effect on capital-based livelihood.

As a last step in the analysis, cluster validation was performed in order to evaluate the goodness of fit of the clustering algorithm results The silhouette width method was used as an internal cluster validation method, which measures how well an observation is clustered by estimating the average distance between clusters (Martin, 2016; Kassambara, 2017). The silhouette plot displays a measure of how close each point in one cluster is to points in the neighboring clusters. Observations with a large silhouette width (almost 1) can be considered well clustered, a small silhouette width means the observation lies within two clusters, and a negative silhouette width means the observation is probably placed in the wrong cluster (Kassambara, 2017).

3.5 Design of livelihood vulnerability index (LVI)

The vulnerability analysis in this study was based on the sustainable livelihoods approach (SLA). SLA can be used to assess vulnerability at the local level by analyzing the status of the five livelihood capitals — financial, social, natural, human, and physical. These five capitals are the basis for assessing an individual's or household's ability to cope with risks. They also serve as a starting point identifying necessary interventions (Chambers and Conway, 1991). Zhang and Fang (2020) inspired our method to construct a Livelihood Vulnerability Index (LVI). They constructed an LVI integrating the 3 dimensions of IPCC's definition of vulnerability—exposure, sensitivity, and adaptive capacity (IPCC, 2014), using the five livelihood capitals from the Department of International Development framework (DFID, 1999). To construct the LVI, each livelihood capital is represented by a number of indicators which belong to one of the three major vulnerability dimensions of livelihood capital: exposure, sensitivity and adaptive capacity. In this study, we first constructed an index of vulnerability for each livelihood capital, which represents the contribution of that specific capital to vulnerability, and then aggregated the scores of the five capital vulnerabilities into one LVI per group of households. This approach indicates how each capital contributes to livelihood vulnerability for each group of farming households.

TABLE 4 Variables used in the cluster analysis.

Livelihood capital	Variable name	Variable code	Type	Range
Human	Household food availability increased due to the adoption of at least one CSA practice	PXW12	Boolean	Yes or no
	Household food diversity increased due to the adoption of at least one CSA practice	PXW13	Boolean	Yes or no
	Percentage of household members that participate in agricultural activities in the household	NUAG	Discrete	0–1
	Percentage of household members who are young (16–30 years old)	NUYO	Discrete	0–1
	Highest education level achieved by household respondent	EDUC	Factor	Secondary or above, primary, none
Natural	Average area destined to productive agricultural activities per household	ARPR	Continuous	200–84,000 (m^2)
	Household depends primarily on on-farm agricultural activities as the main source of income	AGRI_INC	Boolean	Yes or no
	Percentage of adopted soil-improving practices, relative to total soil improving practices offered (e.g., organic fertilizers, crop rotation, residue addition, intercropping, etc.)	SOIL	Discrete	0–1
Physical	Household owns the land destined for agricultural activities	OWNE1	Boolean	Yes or no
	Number of cultivated crop species	CROP_TOTAL	Discrete	0–10
	Number of livestock species	ANIM_TOTAL	Discrete	1–5
	Number of cultivated tree species	TREE_TOTAL	Discrete	0–8
	Percentage of adopted CSA practices relative to total CSA practices offered	PRAX_TOTAL	Discrete	0–1
	Percentage of adopted irrigation systems or practices, relative to total irrigation practices offered (e.g., drip irrigation, water catchments or water ponds for irrigation)	IRRIG	Boolean	0–1
Financial	Household received income from agricultural activities	ICAG	Boolean	Yes or no
	Income from agriculture increased savings in the past year	SVIC	Boolean	Yes or no
	Household accessed a loan or borrowed money for agricultural activities	CREDP	Boolean	Yes or no
	Number of implemented CSA practices that generated extra income for the household	PXW8	Discrete	0–6
Social	Household acquired seasonal climatic information from social networks	CSS1	Boolean	Yes or no
	Household acquired daily or weekly weather information from social networks	CSD1	Boolean	Yes or no
	Household acquired daily or weekly weather information	CSD02	Boolean	Yes or no
	Household acquired seasonal climatic information	CSS02	Boolean	yes or no
	Household received training on CSA practices from a personal or social contact	PRAX_SOC	Boolean	Yes or no

The five capital vulnerability indices and final LVI per group were constructed using 25 sub-component indicators. We selected these indicators based on published studies that measure livelihood vulnerability (Eakin and Bojórquez-Tapia, 2008; Hahn et al., 2009; Pandey and Jha, 2012; Xu et al., 2020; Zhang et al., 2020; Zhang and Fang, 2020). They were also adapted from the variables used in the cluster analyses. To construct the LVI, a balanced weighted average approach was employed, which is based on the assumption that each sub-component equally contributes to the overall index (Hahn et al., 2009).

The whole process to construct the LVI includes four major steps. First, the sub-component indicators were normalized to a value between 0 and 1 by min–max normalization using Eq. 1:

$$Index_{sg} = \frac{S_g - S_{\min}}{S_{\max} - S_{\min}} \quad (1)$$

where S_g is the original investigative indicator sub-component for households in the selected group g, and S_{min} and S_{max} are the minimum and maximum value for each sub-component, respectively.Second, after each sub-component was standardized, Eq. 2 was employed to calculate an index of each dimension of vulnerability (exposure, sensitivity and adaptive capacity) for each type of livelihood capital:

$$Ce_g = \frac{\sum_{i=1}^{n} Index_{sg}}{n}; Cs_g = \frac{\sum_{i=1}^{n} Index_{sg}}{n}; Ca_g = \frac{\sum_{i=1}^{n} Index_{sg}}{n} \quad (2)$$

Where *Ce*, *Cs* and *Ca* correspond to the value of each vulnerability dimension (exposure, sensitivity or adaptive capacity) for each Livelihood Capital of each group *g*. Index *sg* represents the subcomponents, and *n* is the number of sub-components in each of the vulnerability dimensions of Livelihood Capital.

Third, after each dimension of vulnerability was calculated for each type of livelihood capital, Eq. 3 was employed to calculate the index of each Livelihood Capital's contribution to vulnerability (CVI-IPCC):

$$Capital\ Vulnerability\ Index - IPCC_g = (Exposure - Adaptive\ capacity) \times Sensitivity$$

Which can be expressed as:

$$CVI - IPCC_g = (Ce_g - Ca_g) \times Cs_g \quad (3)$$

where *CVI*–*IPCCg* is the value of the Livelihood Capital's overall contribution to vulnerability for group g after incorporating each vulnerability dimension (*Ce*, *Ca*, *Cs*) of the IPCC's vulnerability framework.

Fourth, the LVI at the group-level, which represents the value of the five livelihood capitals for a given group, was calculated using Eq. 4:

$$\begin{aligned} Index_{sg} &= \frac{S_g - S_{\min}}{S_{\max} - S_{\min}} Ce_g = \frac{\sum_{i=1}^{n} Index_{sg}}{n}; Cs_g = \frac{\sum_{i=1}^{n} Index_{sg}}{n}; \\ Ca_g &= \frac{\sum_{i=1}^{n} Index_{sg}}{n} Capital\ Vulnerability\ Index - IPCC_g \\ &= (Exposure - Adaptive\ capacity) \times Sensitivity CVI - IPCC_g \\ &= (Ce_g - Ca_g) \times Cs_g LVI_g = \frac{w_1 HCV + w_2 NCV + w_3 PCV + w_4 FCV + w_5 SCV}{w_1 + w_2 + w_3 + w_4 + w_5} \end{aligned} \quad (4)$$

where w_1, w_2, w_3, w_4, and w_5 are the weights of the five livelihood capitals' contribution to vulnerability—human capital vulnerability (HCV), natural capital vulnerability (NCV), physical capital vulnerability (PCV), financial capital vulnerability (FCV) and social capital vulnerability (SCV). In this study, the LVI ranged from −0.2 (low vulnerability) to 0.4 (high vulnerability). A detailed assessment process of the calculation of the LVI is illustrated in Supplementary material.

The LVI provides a comparable method for assessing vulnerability within groups of CSV farmers. To observe differences in vulnerability associated to CSA adoption, the LVI was constructed for the CSA farmers and the non-CSA farmers. This vulnerability analysis allowed us to observe the different contributions to vulnerability of each livelihood capital and overall LVI of each group of farming households.

4 Results

4.1 Capital-based livelihood vulnerability in CSA vs. non-CSA farmers

The clustering exercise results shed light on three distinct clusters: one comprised of non-CSA farmers and the other two consisting of CSA farmers (refer to Supplementary material for detailed information on the clustering exercise). Within the non-CSA farmer cluster, individuals exhibited the lowest adoption rate of CSA practices, standing at 9.6% for all variables associated with each capital.

In the case of CSA farmers, we performed a two-cluster solution. This clustering approach revealed that the adoption of CSA practices played a pivotal role in delineating different groups within farming households. Subsequent rounds of clustering analysis underscored the primary divergence between the two groups of CSA farmers, which focused primarily on social capital. Cluster 1 showed superior performance in financial and human capital indicators compared to Cluster 2 (see Table 4). Conversely, the non-CSA farmer group displayed markedly lower values across almost all indicators when compared to the two groups of CSA farmers (see Table 5).

The multiple correspondence analysis (MCA) allowed to understand the variables with the largest influence in clustering the data, by underscoring the variables with the largest contributions to the combined first and second dimensions of the analysis (see Supplementary material). These included two variables from human capital (whether household increased food availability, PXW12, and food diversity, PXW13), Four variables from social capital related to acquisition of weather and climatic information and connection with social networks (CSS02, CSD02, CSS1 and CSD1), one variable from physical capital (PRAX_TOTAL: percentage of CSA practices adopted), and one variable from natural capital (SOIL, percentage of soil improving practices adopted). Based on this clustering result the following cluster descriptions were made:

Cluster 1: *Medium-high* adopters of CSA (including soil fertility and food diversity practices), with *high* access to social networks and climate/weather data (82 households).

Cluster 2: *Medium-low* adopters of CSA (including soil fertility and food diversity practices) with *low* access to social networks and climate/weather data (141 households).

Non-CSA: *No-or-low* adopters of CSA (no soil fertility adopters, with low adoption of food diversity practices), *low* access to social networks and *medium* access to climate/weather data (44 households).

The percentage of women responses was similar in the three clusters (35.4% in cluster 1, 28.4% in cluster 2, and 27.3% in the non-CSA cluster) and comparable to the percentage of women responses from the total household sample (30.3%). This result also indicated that, with the household data used in the analysis, gender as

TABLE 5 Summary of cluster information (most influential variables in the clustering based on MCA analysis are highlighted in bold).

Livelihood capital	Variable name and code	CSA farmers		Non-CSA
		Cluster 1	Cluster 2	
Human	**Percentage of households whose food availability increased due to the adoption of at least one CSA practice (PXW12)**	**0.915**	**0.766**	**0.000**
	Percentage of households whose food diversity increased due to the adoption of at least one CSA practice (PXW13)	**0.866**	**0.731**	**0.000**
	Average number of household members that participate in agricultural activities in the household (NUAG)	0.529	0.597	0.512
	Average number of household members who are young (16–30 years old) (NUYO)	0.231	0.231	0.259
	Highest education level achieved by most household (EDUC)	Primary	Primary	Primary
Natural	Average area destined to productive agricultural activities per household (ARPR)	12719	11039	7381
	Percentage of households which depend primarily on on-farm agricultural activities as the main source of income (AGRI_INC)	0.866	0.766	0.750
	Average number of adopted soil-improving practices, relative to total soil-improving practices offered (SOIL)	**0.489**	**0.356**	**0.000**
Physical	Percentage of households which owe the land destined for agricultural activities (OWNE1)	0.671	0.709	0.455
	Average number of cultivated crop species (CROP_TOTAL)	3.476	2.929	2.091
	Average number of livestock species (ANIM_TOTAL)	1.183	0.915	0.568
	Average number of cultivated tree species (TREE_TOTAL)	2.073	2.433	1.318
	Average number of adopted CSA practices relative to total CSA practices offered (PRAX_TOTAL)	**0.417**	**0.292**	**0.000**
	Average number of adopted irrigation systems or practices, relative to total irrigation practices offered (e.g., drip irrigation, water catchments or water ponds for irrigation) (IRRIG)	0.309	0.200	0.000
Financial	Percentage of households which received income from agricultural activities (ICAG)	0.902	0.823	0.841
	Percentage of households which were able to have savings from agriculture in the past year (SVIC)	0.329	0.227	0.409
	Percentage of households which accessed a loan or borrowed money for agricultural activities (CREDP)	0.488	0.248	0.250
	Average number of implemented CSA practices that generated extra income for the household (PXW8)	0.793	0.532	0.000
Social	**Percentage of households which acquired seasonal climatic information from social networks (CSS1)**	**0.805**	**0.028**	**0.182**
	Percentage of households which acquired daily or weekly weather information from social networks (CSD1)	**0.793**	**0.021**	**0.091**
	Percentage of households which acquired daily or weekly weather information (CSD02)	**1.000**	**0.227**	**0.500**
	Percentage of households which acquired seasonal climatic information (CSS02)	**0.963**	**0.234**	**0.545**
	Percentage of households which received training on CSA practices from a personal or social contact (PRAX_SOC)	0.805	0.816	0.227

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a variable for clustering did not show a significant influence in the partitioning of the data. It is possible that gender could have higher influence in the clustering than the one observed in this analysis, had the percentage of female respondents from the clustering sample been higher. Despite the relevance for this type of studies, the lack of systematic recording of one male and one female survey per household limited the possibility to analyse gender implications. The latter in addition to the significant amount of missing and incorrect data, which forced to discard many household records from the initial datasets.

Figures 1, 2 present the constructed capital vulnerability scores for each group of households, and the disaggregated indicator values per capital and per dimension of vulnerability. The final aggregated Livelihood Vulnerability Index (LVI) score for each group of households reveals that CSA Cluster 1 exhibits the lowest livelihood vulnerability (−0.048), followed by CSA Cluster 2 (0.063), with the non-CSA farmers group displaying the highest vulnerability (0.168).

In a comprehensive overview, CSA Cluster 1 demonstrates the lowest vulnerability across all types of capital, except for natural capital, where CSA Cluster 2 shows a slightly lower vulnerability (0,007 compared to −0.012, respectively). On the contrary, the non-CSA farmers group registers the highest vulnerability across all types of capital, despite scoring similarly to CSA Cluster 2 in social, financial, and physical capital (Figure 1). Regarding the impact of each livelihood capital on vulnerability, the three groups of farming households demonstrated comparable performance in terms of financial and physical capital. However, even within these two capital categories, CSA Cluster 1 outperformed the other two clusters, as illustrated in Figure 1.

The largest differences between the three groups of farming households were observed for social, human, and natural capital. For human and natural, the two CSA clusters showed similar and much lower vulnerability scores (human: 0.000 and 0.043; natural: 0.007 and 0.012, respectively) than the group of non-CSA farmers (human: 0.359; natural: 0.171). In terms of social capital, CSA cluster 1 showed by far the lowest vulnerability among groups (−0.152) whereas CSA cluster 2 and non-CSA farmers showed a similar and much higher vulnerability score in social capital (0.264 and 0.304, respectively) (Figures 1, 2).

4.2 Human capital

The differences in human capital scores between CSA farmers and non-CSA farmers were mainly due to the different performance in the food availability and food diversity indicators, for which non-CSA farmers showed high vulnerability (Figures 1, 2). This result suggests that CSA interventions might be particularly effective in improving food diversification in the farming household for either on-farm consumption or market sales. Furthermore, a slightly higher percentage of CSA farmers achieved a higher education index. However, educational differences between farming households might have already been present prior to CSA interventions. A wider range of indicators for human capital could be included to characterize this type of capital. Then, we might observe larger differences between groups of farming households and where the differences come from. Other possible indicators to be included in the quantification of human capital could be the dependency ratio, the percentage of illiteracy in the household, the level of education, agricultural training of the members of the household, and the overall health of household members (Xu et al., 2020; Zhang et al., 2020; Zhang and Fang, 2020).

4.3 Natural capital

Non-CSA farmers did not adopt any soil-improving practices, which resulted in the main difference in natural capital scores among groups (Figure 2). However, is it possible that the group of non-CSA farmers has adopted or already implemented other soil conservation practices than the soil practices included in the CSA package, and therefore have a higher adaptive capacity in natural capital than what our indicator reflects. Another observed difference in natural capital between groups was the average area destined to productive agricultural activities per household, which was higher in CSA

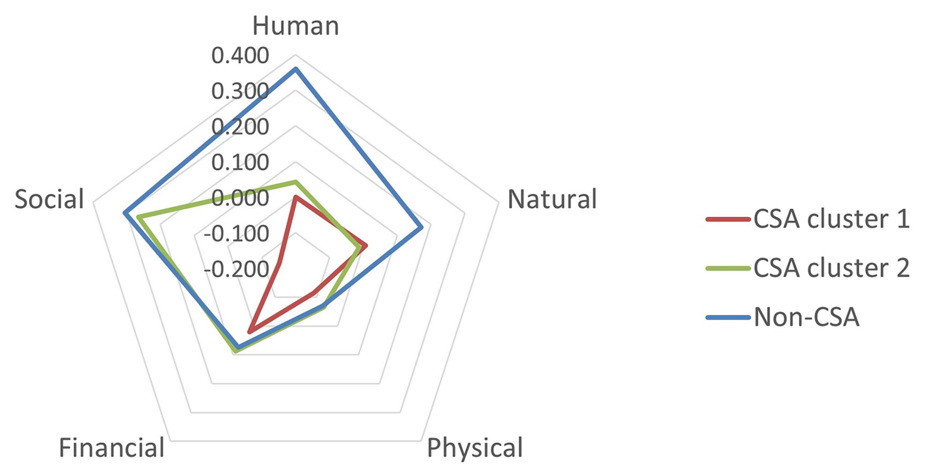
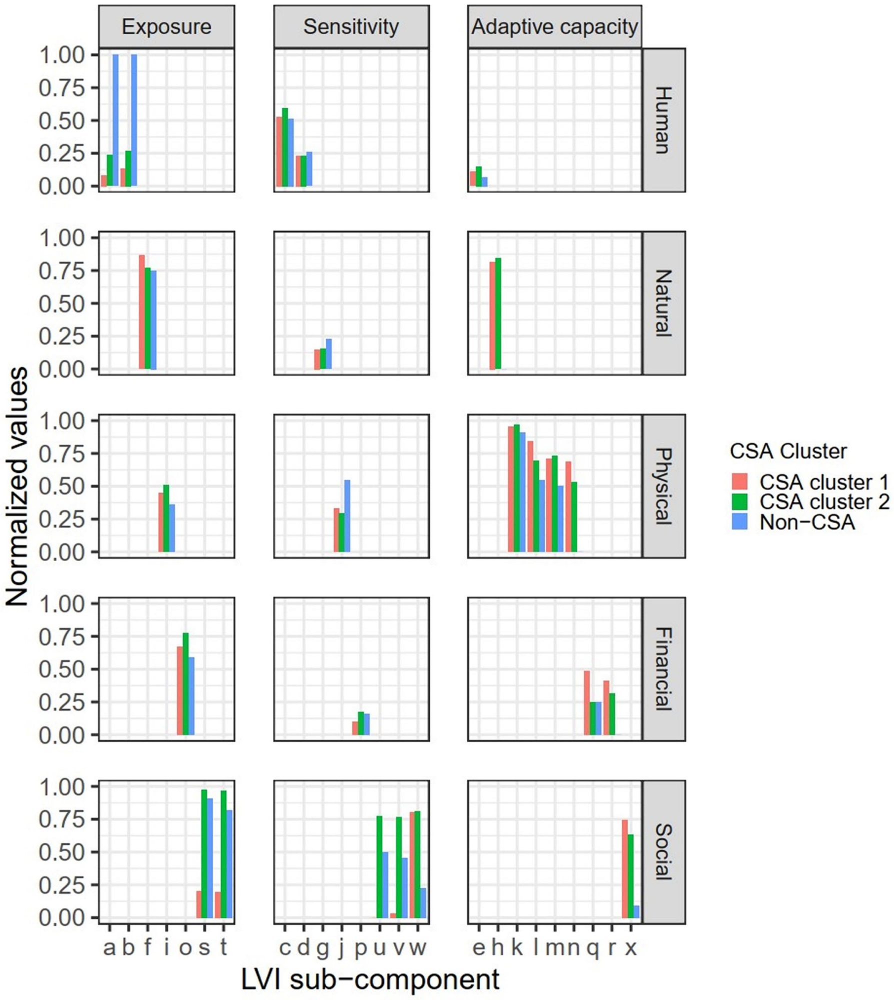


FIGURE 1
Livelihood vulnerability results per livelihood capital for the three groups of climate-smart village farming households: CSA farmers-cluster 1 (red), CSA farmers-cluster 2 (green), and CSA non-farmers (blue; −0.2 = least vulnerable, 0.4 = most vulnerable).



a	% of HH that have not increased food availability.	i	Av. number of HH-owned goods (tree, crops, and animal species).	q	% of HH who accessed a loan or borrowed money for agricultural activities.
b	% of HH that have not increased food diversity.	j	% of HH that do not own the land destined for agricultural activities.	r	% of HH which generated extra income from the adoption of CSA practices.
c	Av. number of HH members participating in HH agricultural activities	k	% of HH with cultivated land.	s	% of HH that do not acquire daily or weekly weather information from social networks.
d	Av. number of young household members (16 to 30 y/o).	l	% of HH with livestock.	t	% of HH that do not acquire seasonal climatic information from social networks.
e	Education index (% of HH that has completed secondary or above).	m	% of HH with cultivated trees.	u	% of HH with difficulty accessing daily or weekly weather information.
f	% of HH dependent primarily on on-farm agriculture as a main source of income.	n	% of HH that adopted irrigation systems or practices.	v	% of HH with difficulty accessing seasonal climatic information.
g	Av. area destined to productive agricultural activities per HH.	o	% of HH which could not have savings from agriculture in the past year.	w	% of HH who received training on CSA practices from a personal or social contact.
h	% of HH that adopted soil-improving practices.	p	% of HH which did not receive income from agricultural activities.	x	% of HH involved in social groups.

FIGURE 2
Normalized indicator values for livelihood capitals and dimension of vulnerability, for three types of CSV farming households: two groups of CSA farmers and non-CSA farmers. Further details on indicator values see Supplementary material.

farmers compared to non-CSA farmers (Figure 2). This result suggests that agricultural land differences between CSA adopters and non-adopters might have already been present. However, since the indicator used corresponded to the area destined to productive agricultural activities and not the total farm size, it is also possible that CSA might have had a positive effect in supporting farmers in more efficiently utilizing their existing land for agricultural production. Nevertheless, this livelihood capital only included three indicators, one for each dimension of vulnerability, which greatly limits the ability to fully measure natural capital-related differences between groups. More indicators should be included to cover all aspects of this capital, including indicators about access to fresh water sources, quality of the owned land, exposure to climatic events, biodiversity degree, air quality, erosion protection, etc. (Xu et al., 2020; Zhang and Fang, 2020; Zhang et al., 2020).

4.4 Physical capital

The largest difference in physical capital between groups was the percentage of adopted irrigation practices, which was 0% for non-CSA farmers and 60 and 50% for the two groups of CSA farmers, respectively (Figure 2). This result suggests that CSA might have positively encouraged farmers to adopt improved water management practices. However, as for the adoption of soil-improving practices, it is possible that non-CSA farmers already have some irrigation practices or infrastructure in place that this indicator would not measure. The second largest difference in physical capital was the percentage of households which do not own the land dedicated to agricultural activities, which was higher in non-CSA farmers (50%) and relatively similar between the two groups of CSA farmers (33 and 29%). This result suggests that differences in land property rights might have already been present prior to CSA implementation. It is possible that households who are owners might have been at an advantage in their ability to take up CSA practices. The average number of household-owned goods was similar between the two groups of CSA farmers and higher than the non-CSA group (Figure 2). All three groups showed a similar percentage of households with cultivated land (above 90% in all cases), but a higher percentage of households in CSA cluster 1 had livestock compared to CSA cluster 2 and non-CSA farmers, suggesting the CSA focus on farm diversification improved resilience. The two CSA groups also showed a higher percentage of households with cultivated tree species. Although six indicators were used to measure physical capital, our set of indicators did not cover other relevant aspects for this type of capital, such as possession of agricultural machinery and other durable goods, the level of infrastructure, transport, access to markets, etc. To better quantify physical capital, further indicators which measure these aspects should also be included (DFID, 1999; Xu et al., 2020; Zhang and Fang, 2020; Zhang et al., 2020).

4.5 Financial capital

Adaptive capacity indicators described the largest differences in financial capital between groups. The two groups of CSA farmers were in general more able to borrow money or were able to generate extra sources of income compared to the group of non-CSA farmers. This result again highlights the potential positive effect of CSA implementation on food and income diversification. The percentage of households which were unable to save money in the past year was more similar among all groups but still higher for the CSA farmers than non-CSA farmers. A lower number of households did not receive income from agriculture in CSA cluster 1 (9.8%) compared to the other two groups (17.7 and 15.9%). Other possible indicators related to non-farm income sources are if the household experienced monetary loss or if the household is below the poverty line. The analysis could benefit from indicators on insurance, subsidies, total annual income or other types of financial support (DFID, 1999; Xu et al., 2020; Zhang and Fang, 2020; Zhang et al., 2020).

4.6 Social capital

Social capital was the livelihood capital where the largest differences between groups of farming households were observed. Almost no household from CSA cluster 1 had difficulty accessing weather information whether daily or seasonal, whereas 70 and 50% of households in CSA cluster 2 and non-CSA, respectively, could not access this information (Figure 2). Furthermore, a high percentage of households in CSA cluster 1 acquired weather and climate information from social networks, which was not the case for the other two groups. This result suggests that CSA interventions might have been most successful in farming communities with already-established social networks. When these networks were not as strong, the positive CSA contribution in social capital might have been minimal. The involvement of households in social groups was much higher for CSA farmers (74 and 64%, respectively) than in non-CSA farmers (10%). Other possible indicators that could be included to better characterize social capital would be percentage of households with members working for the government, households receiving help from the government, number of community organizations joined, or diversity of agricultural product sales channels (DFID, 1999; Xu et al., 2020; Zhang and Fang, 2020; Zhang et al., 2020).

5 Discussion and conclusion

This study seeks to explain the contribution of CSA to the sustainability of rural livelihoods in Latin America. Leveraging field data from three distinct geographies in Latin America, we conduct a comparative analysis of the Climate-Smart Village (CSV) approach, evaluating the resilience of rural livelihoods. An innovative aspect of our study involves the integration of CSA and the Sustainable Livelihoods Framework (SLF), providing a nuanced perspective on the impact of CSA. The insights garnered from this research have significant implications for informing policy and investment decision-making processes.

Our findings underscore the positive impact of CSA practices on diverse livelihood capitals. Noteworthy outcomes include improved indicators of food availability and diversity (human capital) among CSA farmers. Additionally, CSA farmers show a propensity to adopt soil-improving practices acquired from social networks, thereby enhancing their natural capital. Geographical disparities in the adoption of irrigation practices reveal significant differences in physical capital among CSA farmers. Financially, CSA farmers show higher adaptive capacity, particularly in accessing credit and generating income. Socially, there is a pronounced increase in the participation of CSA farmers in social groups, reflecting enhanced social capital, which is confirmed by Das et al. (2023) who found that households with stronger social assets are more resilient to climatic challenges. Previous studies also highlight the value of a combined CSA approach and SLA focus to enhance resilience to climate change and livelihoods by identifying the most effective CSA practices per region (Mathews et al., 2018; Ogola and Ouko, 2021; Muzorewa and Chitakira, 2022). Other studies have gone further in these analyzes by measuring the contribution of specific CSA practices to the three CSA pillars, as a proxy to measure contribution to sustainable livelihoods (Ogola and Ouko, 2021; Tilahun et al., 2023).

The combination of CSA and SLA approaches to assess resilience has therefore been mostly studied from a CSA entry point. In contrast, other studies have focused on using the SLA approach to assess contribution to climate change resilience in different agricultural communities (Das et al., 2023). This study broadens the methodologies and evidence by providing a dual framework to delineate which aspects of livelihoods need to be enhanced most in CSA rural agricultural communities. Collectively, these results affirm that building the capacity to adapt to climate change is closely linked to the multiple capitals of rural livelihoods.

Our study highlights that, within the Latin American farming households included in the analysis, the CSV approach has had an overall positive impact on reducing livelihood vulnerability. Fuchs et al. (2019) and Mathews et al. (2018) highlight the notable positive impact on the sustainability of livelihoods and landscapes when appropriate and targeted CSA measures are implemented. However, the analysis also highlights that the CSV approach was particularly successful in increasing natural and human capital, somewhat successful in improving social capital, and had almost no effect in improving physical and financial capital.

This uneven contribution to capital-based vulnerability could be due to CSV's focus on implementing CSA practices that improve agrobiodiversity, agricultural management practices, and access to information and social networks which can have a large impact on natural, human, and social capital, respectively. The increase in these three key capitals suggests that CSA can positively contribute to increasing resilience to climate change, as resilience can be increased with more diversified farming systems (Vernooy, 2022) and a wider support network (Ingold, 2017).

The limited impact of CSA interventions on financial and physical capital highlights the need to include additional interventions within or alongside this approach. Interventions should help farmers address these two key aspects of livelihood vulnerability. Other studies have also highlighted the important contribution of income diversification CSA strategies to strengthen financial capital and resilience, particularly in lower income households (Berhanu et al., 2021). The analysis suggests that the CSV approach either did not sufficiently target improvements in farmers' financial and physical capital, or it failed to address differences that might have already been present (such as differences in farm size and land rights). Additional interventions to specifically target farmers' financial and physical capital could include the introduction of financial instruments such as subsidies (for inputs, infrastructure, or machinery), loans, grants or insurance. Our study sheds light on the interplay between climate-resilient agriculture and sustainable livelihoods by integrating the SLF and CSA. It underscores the need for a comprehensive lens to fully assess the impact of CSA on rural livelihoods. However, it is important to further characterize differences in impact of CSA on the livelihoods of rural women and men, which was a limitation of this study due to a lack of sufficient gender disaggregated data for the statistical analysis.

Our results on social capital support previous findings on the role of social networks in enabling interactions across scales that can support CSA adoption (Martinez-Barón et al., 2018). However, the role of gender in establishing and maintaining these social networks needs to be better understood. Not only is it important to better understand the role of gender within social capital, but its role in all five livelihood capitals, as well as the relationship between gender and the three aspects of livelihood vulnerability. Further research should advance these findings by considering and comparing the perspectives of both men and women within CSA and non-CSA rural communities, and how they contribute to improve livelihoods and enhance resilience Moreover, not only gender differences in CSA adoption should be further looked at, but also how other intersecting factors such as socio-economic level, age, or education level, interact with gender to drive or halt CSA adoption (Howland et al., 2019; Acosta et al., 2021).

In this study, it was not possible to conduct such disaggregated analysis due to having an insufficient women sample size, which we acknowledge as a limitation. Equally important is the need to understand not only the relationship between gender and livelihood vulnerability, but also identify key areas of intervention where the rights of smallholder women can be advanced. Such advancement of women's rights could begin by better understanding gender norms in smallholder agriculture and using novel frameworks for system change towards resilience (Rietveld et al., 2023). We acknowledge the pivotal role of women in increasing resilience in small-scale agriculture, and suggest putting gender at the centre of AR4D studies from the very initial stages of project design (IFAD, 2022). We especially emphasize the importance of centering gender during hypothesis formulation, and data collection methodology definition, in order to ensure a higher recording of female household responses to better capture the perspectives of rural women in both qualitative and quantitative ways. We emphasize again the importance of adopting a dual framework for policy and investment decisions, recognizing the complementary insights provided by both CSA and SLF.

Special consideration also needs to be taken to understand why the CSV approach succeeded in increasing social capital for some CSA farmers, but not for all, and the potential role of gender in this regard. Other combined CSA and SLA approaches in other regions also report that higher project involvement predicts lower livelihood vulnerability (Fuchs et al., 2019). This analysis suggests that the CSV approach can increase social capital very significantly by linking farmers to social groups and to information services. However, practitioners should carefully examine what factors play a role in livelihood capital formation for some CSA farmers and not others.

In conclusion, our research highlights the potential for CSA to positively influence rural livelihoods in the LAC region. The study advocates for continued research efforts, incorporating expanded indicators, such as gender indicators within social and human capital definitions, for a more comprehensive assessment of CSA's impact. Additionally, we stress the urgency of considering the implications for promoting sustainable livelihoods in the face of climate change. This comprehensive approach is vital for guiding effective policies and investments geared towards building resilient and sustainable rural communities in LAC.

Data availability statement

The data used in the study corresponds to three published datasets containing household survey information from the "Integrated Monitoring Framework for Climate-Smart Agri- culture" from the CCAFS research project (Bonilla-Findji et al., 2020a,b,c).

Ethics statement

The studies involving humans were approved by the Institutional Review Board (IRB) of the Alliance of Bioversity and CIAT. The IRB chairs are Juliana Muriel and Powell Mponela. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

DMB: Conceptualization, Funding acquisition, Investigation, Methodology, Resources, Supervision, Validation, Writing – original draft, Writing – review & editing. MA: Data curation, Formal analysis, Methodology, Writing – original draft, Software, Visualization, Writing – review & editing. JM: Conceptualization, Investigation, Formal analysis, Methodology, Supervision, Validation, Writing – original draft. AC: Investigation, Writing – review & editing.

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Conflict of interest

MA was employed by FarmTree B.V.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1363101/full#supplementary-material

References

Acosta, M., Riley, S., Bonilla-Findji, O., Martínez-Barón, D., Howland, F., Huyer, S., et al. (2021). Exploring women's differentiated access to climate-smart agricultural interventions in selected climate-smart villages of Latin America. *Sustain. For.* 13:10951. doi: 10.3390/su131910951

Berhanu, Y., Vedeld, P., Angassa, A., and Aune, J. B. (2021). The contribution of frankincense to the agro-pastoral household economy and its potential for commercialization – a case from Borana, southern Ethiopia. *J. Arid Environ.* 186:104423. doi: 10.1016/j.jaridenv.2020.104423

Bonilla-Findji, O., Eitzinger, A., Andrieu, N., Jarvin, A., Martínez- Barón, D., Ortega, L. A., et al. (2019). "2018- CSA Monitoring – Cauca Climate Smart-Village Colombia", Harvard Dataverse, V2, UNF:6:DmhB4LLks9al/lk0KgS72Q== [fileUNF]. CCAFS Dataset. CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS). doi: 10.7910/DVN/FNWDAX

Bonilla-Findji, O., Eitzinger, A., and Andrieu, N. (2021). Implementation manual: CCAFS climate-smart monitoring framework – tackling uptake of CSA options and perceived outcomes at household and farm level. CGIAR research program on climate change, agriculture and food security (CCAFS). Implementation in the AR4D climate-Smart Village sites: pp. 9–11.

Bonilla-Findji, O., Eitzinger, A., Andrieu, N., Jarvis, A., Martínez-Barón, D., Martínez-Salgado, J. D., et al. (2020a) 2020 – CSA monitoring: Santa Rita climate-Smart Village (Honduras). Harvard Dataverse, V1, UNF:6:r8DXvNJlyJAczxH+fFbNcQ== [fileUNF]. doi: 10.7910/DVN/OSNTKT

Bonilla-Findji, O., Eitzinger, A., Jarvis, A., Andrieu, N., Martínez-Barón, D., Martínez-Salgado, J. D., et al. (2020b). 2020 – CSA monitoring: Olopa climate-Smart Village (Guatemala). Harvard Dataverse, V1, UNF:6:pN+7CErDRSwYGPDXjBoQYw== [fileUNF]. doi: 10.7910/DVN/VTPO4U

Bonilla-Findji, O., Eitzinger, A., Jarvis, A., Martínez-Barón, D., Martínez-Salgado, J. D., Ortega, L. A., et al. (2020c). 2019 – CSA monitoring – Cauca climate Smart-Village (Colombia). Harvard Dataverse, V2, UNF:6:L8DWb+pzT5t++8r30hoa3A== [fileUNF]. doi: 10.7910/DVN/ZHEDWC

Chadalavada, K., Kumari, B. D. R., and Kumar, T. S. (2021). Sorghum mitigates climate variability and change on crop yield and quality. *Planta* 253:113. doi: 10.1007/s00425-021-03631-2

Chambers, R., and Conway, G. R. (1991). Sustainable rural livelihoods: Practical concepts for the 21st century. IDS discussion paper, 296 (Brighton: Institute of Development Studies, University of Sussex), 29.

Chávez Esponda, D., Miranda Cabrera, I., Varela Nualles, M., and Fernández, L. (2010). Utilización del análisis de cluster con variables mixtas en la selección de genotipos de maíz (*Zea mays*). *Rev. Investig. Oper.* 30, 209–216.

Das, U., Ansari, M. A., and Ghosh, S. (2023). Measures of livelihoods and their effect on vulnerability of farmers to climate change: evidence from coastal and non-coastal regions in India. *Environ. Dev. Sustain.* 26, 4801–4836. doi: 10.1007/s10668-023-02911-z

DFID. (1999). DFID (2000): Sustainable livelihoods guidance sheets. Department for International Development. Available at: http://www.livelihoods.org/info/info_guidancesheets.html

Donatti, C. I., Harvey, C. A., Martinez-Rodriguez, M. R., Vignola, R., and Rodriguez, C. M. (2019). Vulnerability of smallholder farmers to climate change in Central America and Mexico: current knowledge and research gaps. *Clim. Dev.* 11, 264–286. doi: 10.1080/17565529.2018.1442796

Doss, C. R. (2018). Women and agricultural productivity: reframing the issues. *Dev. Policy Rev.* 36, 35–50. doi: 10.1111/dpr.12243

Eakin, H., and Bojórquez-Tapia, L. A. (2008). Insights into the composition of household vulnerability from multicriteria decision analysis. *Glob. Environ. Chang.* 18, 112–127. doi: 10.1016/j.gloenvcha.2007.09.001

FAO. (2013). Climate-smart agriculture sourcebook. Rome. Available at: https://www.fao.org/publications/card/en/c/6f103daf-4cd2-5a95-a03c-3d5d6b489fff/

Fuchs, L., Orero, L., Namoi, N., and Neufeldt, H. (2019). How to effectively enhance sustainable livelihoods in smallholder systems: a comparative study from western Kenya. *Sustain. For.* 11:1564. doi: 10.3390/su11061564

Gentle, P., and Maraseni, T. (2012). Climate change, poverty and livelihoods: adaptation practices by rural mountain communities in Nepal. *Environ. Sci. Pol.* 21, 24–34. doi: 10.1016/j.envsci.2012.03.007

Gitz, V., Meybeck, A., Lipper, L., De Young, C., and Braatz, S. (2016). Climate change and food security: risks and responses. Food and Agriculture Organization of the United Nations 110, pp. 2–4. Available at: https://www.fao.org/3/i5188e/I5188E.pdf

Habib, N., Ariyawardana, A., and Aziz, A. A. (2023). The influence and impact of livelihood capitals on livelihood diversification strategies in low- and middle-income countries: a systematic literature review. *Environ. Sci. Pollut. Res.* 30, 69882–69898. doi: 10.1007/s11356-023-27638-2

Hahn, M. B., Riederer, A. M., and Foster, S. O. (2009). The livelihood vulnerability index: a pragmatic approach to assessing risks from climate variability and change-a case study in Mozambique. *Glob. Environ. Chang.* 19, 74–88. doi: 10.1016/j.gloenvcha.2008.11.002

Hendrickson, J. L. (2014). Methods for clustering mixed data. 109. Available at: http://scholarcommons.sc.edu/cgi/viewcontent.cgi?article=3651&context=etd

Howland, F., Arora, D., Bonilla-Findji, O., and Andrieu, N. (2019). Understanding socio-economic aspects of adoption and effects of climate smart agricultural (CSA) practices in Guatemala. Cali, Colombia: CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS).

IFAD. (2022). How to do note: How to integrate the gender action learning system (GALS) in IFAD operations.

IICA (2019). Atlas for Agriculture in the Americas. Available at: http://repositorio.iica.int/handle/11324/8218

Ingold, K. (2017). How to create and preserve social capital in climate adaptation policies: a network approach. *Ecol. Econ.* 131, 414–424. doi: 10.1016/j.ecolecon.2016.08.033

IPCC (2014). Climate change 2014: synthesis report. Contribution of working groups I, II and III to the fifth assessment report of the intergovernmental panel on climate change [Core writing team, R.K. Pachauri and L.A. Meyer (eds.)].

Kassambara, A. (2017). Multivariate analysis 1: practical guide to cluster analysis in R: Taylor & Francis Group, 1–187.

Lal, R., Delgado, J. A., Groffman, P. M., Millar, N., Dell, C. J., and Rotz, A. C. (2011). Management to mitigate and adapt to climate change. *J. Soil Water Conserv.* 66, 276–285. doi: 10.2489/jswc.66.4.276

Lipper, L., Thornton, P., Campbell, B. M., Baedeker, T., Braimoh, A., Bwalya, M., et al. (2014). Climate-smart agriculture for food security. *Nat. Clim. Chang.* 4, 1068–1072. doi: 10.1038/nclimate2437

Lipper, L., and Zilberman, D. (2018). A short history of the evolution of the climate smart agriculture approach and its links to climate change and sustainable agriculture debates. In: L. Lipper, N. McCarthy, D. Zilberman, S. Asfaw and G. Branca (eds) Climate smart agriculture: Building resilience to climate change, 13–30. Available at: https://link.springer.com/chapter/10.1007/978-3-319-61194-5_2#Sec4

López, C., Álvarez, O., Martínez-Salgado, J. D., and Martínez Barón, D. (2020). Manual de implementación de prácticas de Agricultura Sostenible Adaptada al Clima (ASAC). Experiencias de los TeSAC de Guatemala y Honduras. Programa de Investigación de CGIAR en Cambio Climático, Agricultura y Seguridad Alimentaria (CCAFS). Available at: https://hdl.handle.net/10568/111802

Manda, J., Alene, A. D., Gardebroek, C., Kassie, M., and Tembo, G. (2016). Adoption and impacts of sustainable agricultural practices on maize yields and incomes: evidence from rural Zambia. *J. Agric. Econ.* 67, 130–153. doi: 10.1111/1477-9552.12127

Martin, D. P. (2016). Clustering mixed data types in R. Accessed from Wicked Good Data (dpmartin42.github.io)

Martinez-Barón, D., Orjuela, G., Renzoni, G., Rodríguez, A. M. L., and Prager, S. D. (2018). Small-scale farmers in a 1.5 C future: the importance of local social dynamics as an enabling factor for implementation and scaling of climate-smart agriculture. *Curr. Opin. Environ. Sustain.* 31, 112–119. doi: 10.1016/j.cosust.2018.02.013

Martínez-Salgado, J. D., and Alvarez, O. (2020). Implementación del Monitoreo de opciones de Agricultura Sostenible Adaptada al Clima (ASAC): Seguimiento a su adopción e impactos en el TeSAC de Santa Rita, Honduras. – Reporte de Actividad. Wageningen, the Netherlands: Programa de Investigación del CGIAR en Cambio Climático, Agricultura y Seguridad Alimentaria (CCAFS). Available at: https://hdl.handle.net/10568/109696

Martínez-Salgado, J. D., and López, C. (2020) Implementación del Monitoreo de opciones de Agricultura Sostenible Adaptada al Clima (ASAC): Seguimiento a su adopción e impactos en el TeSAC de Olopa, Guatemala – febrero 2020 Reporte de Actividad. Wageningen, the Netherlands: Programa de Investigación del CGIAR en Cambio Climático, Agricultura y Seguridad Alimentaria (CCAFS). Available at: https://hdl.handle.net/10568/109696

Mathews, J. A., Kruger, L., and Wentink, G. J. (2018). Climate-smart agriculture for sustainable agricultural sectors: the case of Mooifontein. *Jamba (Potchefstroom, South Africa)* 10. doi: 10.4102/jamba.v10i1.492

Muzorewa, W., and Chitakira, M. (2022). "Evaluating the role of climate smart agriculture towards sustainable livelihoods in Mutare district, Zimbabwe". Universität Kassel. doi: 10.17170/KOBRA-202110144900

Ogola, R. J. O., and Ouko, K. O. (2021). Synergies and trade-offs of selected climate smart agriculture practices in Irish potato farming, Kenya. *Cogent Food Agric.* 7. doi: 10.1080/23311932.2021.1948257

Pandey, R., and Jha, S. K. (2012). Climate vulnerability index – measure of climate change vulnerability to communities: a case of rural lower Himalaya, India. *Mitig. Adapt. Strateg. Glob. Chang.* 17, 487–506. doi: 10.1007/s11027-011-9338-2

R Core Team. (2020). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available at: https://www.R-project.org/

Ray, D. K., West, P., Clark, M., Gerber, J., Prishchepov, A. V., and Chatterjee, S. (2019). Climate change has likely already affected global food production. *PLoS One* 14:e0217148. doi: 10.1371/journal.pone.0217148

Ricciardi, V., Ramankutty, N., Mehrabi, Z., Jarvis, L., and Chookolingo, B. (2018). How much of the world's food do smallholders produce? *Glob. Food Sec.* 17, 64–72. doi: 10.1016/j.gfs.2018.05.002

Rietveld, A. M., Farnworth, C. R., Shijagurumayum, M., Meentzen, A., Voss, R., Morahan, R., et al. (2023). An evidence synthesis of gender norms in agrifood systems: pathways towards improved women's economic resilience to climate change. Bioversity International. Rome, Italy. 90 p. ISBN: 978–92–9255-310-4

Singh, N. P., Anand, B., Singh, S., Srivastava, S. K., Rao, C. S., Rao, K. V., et al. (2021). Synergies and trade-offs for climate-resilient agriculture in India: an agro-climatic zone assessment. *Clim. Chang.* 164, 1–2. doi: 10.1007/s10584-021-02969-6

Tilahun, G., Bantider, A., and Yayeh, D. (2023). Synergies and trade-offs of climate-smart agriculture (CSA) practices selected by smallholder farmers in Geshy watershed, Southwest Ethiopia. *Reg. Sustain.* 4, 129–138. doi: 10.1016/j.regsus.2023.04.001

Vernooy, R. (2022). Does crop diversification lead to climate-related resilience? Improving the theory through insights on practice. *Agroecol. Sustain. Food Syst.* 46, 877–901. doi: 10.1080/21683565.2022.2076184

Xu, X., Wang, L., Sun, M., Fu, C., Bai, Y., Li, C., et al. (2020). Climate change vulnerability assessment for smallholder farmers in China: an extended framework. *J. Environ. Manag.* 276:111315. doi: 10.1016/j.jenvman.2020.111315

Yin, S., Yang, X., and Chen, J. (2020). Adaptive behavior of farmers' livelihoods in the context of human-environment system changes. *Habitat Int.* 100:102185. doi: 10.1016/j.habitatint.2020.102185

Zhang, C., and Fang, Y. (2020). Application of capital-based approach in the measurement of livelihood sustainability: a case study from the Koshi River basin community in Nepal. *Ecol. Indic.* 116:106474. doi: 10.1016/j.ecolind.2020.106474

Zhang, H., Zhao, Y., and Pedersen, J. (2020). Capital assets framework for analyzing household vulnerability during disaster. *Disasters* 44, 687–707. doi: 10.1111/disa.12393

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CacaoFIT: the network of cacao field trials in Latin America and its contribution to sustainable cacao farming in the region

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A network of agronomists, researchers, and practitioners associated with cacao farming provided open access to their independent field trials across Latin America and the Caribbean (LAC). A centralized dataset was assembled using qualitative and quantitative data from 25 experimental field trials (hereafter referred to as "CacaoFIT") spanning several LAC agroecosystems. This dataset was used to document the main traits and agroclimatic attributes of the cacao cultivation model being tested within the CacaoFIT network. By synthesizing data from an entire network of cacao trials, this study aimed to highlight specific design features and management practices that may contribute to better cacao farming sustainability. The CacaoFIT network comprises 200 ha of field trials testing over 150 cacao genotypes and set up under different shade canopy design, management, and research goals. Small-sized trials were common across Mesoamerica, whereas medium to large-size trials were distinct to South America. Cacao trials were 15 years old (on average) and ranged from 3 to 25 years of establishment. Most cacao trials were managed conventionally (i.e., 55%), while 20% were under organic practices, and the remaining 25% presented both conventional and organic management approaches. Most field trials (ca. 60%) planted an average of 10 international clones or national cultivars at high (1,230–1,500 plants ha^{-1}) and medium density (833–1,111 plants ha^{-1}). Mixed shade canopies were the dominant agroforestry model, while timber vs. leguminous shade canopies were also common. The diversity and depth of research domains examined across the CacaoFIT network varied widely. Agronomy and agroforestry topics dominated the research agenda across all trials, followed by environmental services domains. Cacao physiology and financial performance were researched to a lesser extent within the network. Five featured field trials from CacaoFIT offered technical guidelines to inform cacao farming within similar contexts. This collaborative work is a scaffold to encourage public–private partnerships, capacity building, and data sharing amongst cacao researchers across the tropics.

KEYWORDS

agroforestry, cacao trials, on-farm research, perennial crops, sustainability

Introduction

Globally, cocoa cultivation covers over 11 million hectares of land (Fountain, 2022; Hütz-Adams et al., 2022). It is estimated that about 33% of cocoa is cultivated under shade conditions (i.e., agroforestry systems) (Somarriba and López, 2018b). Latin America and the Caribbean (LAC) is the third largest cacao cultivation region worldwide, with 1.2 million ha grown under different cropping systems (ranging from full sun to rustic cacao) (Somarriba and Lachenaud, 2013; Orozco-Aguilar et al., 2021; Daymond et al., 2022). Cacao cultivation in LAC sustains the livelihoods of ~1.7 million small farmers, provides key environmental services, and plays a pivotal role in landscape restoration efforts (Deheuvels et al., 2012; Cerda et al., 2014; Middendorp et al., 2018; Niether et al., 2018; Garcia-Briones et al., 2021; Notaro et al., 2021; Hütz-Adams et al., 2022). Major threats to a thriving cacao industry in LAC are aging cacao plantations and farmers, lack of access to finance for renovation/rehabilitation, reduced availability of high-quality planting material, new pests and disease outbreaks, risk of cadmium contamination, lack of market channels for agroforestry products, soil fertility decline, low crop productivity, and new cero-deforestation regulation (Jacobi et al., 2014; Vaast and Somarriba, 2014; Chavez et al., 2015; Dalberg, 2015; Cilas and Bastide, 2020; Wiegel et al., 2020; Ceccarelli et al., 2021; Solidaridad, 2023; Thomas et al., 2023).

There are two major scenarios of cacao farming and trading models in LAC. In one scenario, smallholder farmers (≤10 ha farmland) grow mostly seed-based and rain-fed cacao plots with low planting density, unknown compatibility of grown cacao varieties, suboptimal shade canopy design, modest pruning, weeding, and harvesting management (Cerda et al., 2014; Somarriba et al., 2018; Garcia-Briones et al., 2021; López-Cruz et al., 2021; Notaro et al., 2021). In the other scenario, medium- and large-size cacao plantations (over 100 ha farmland) grow improved cacao planting material on irrigated plots with a simplified shade canopy, regular fertilization, and timely agricultural management (Hartemink, 2005; Jacobi et al., 2014; Wiegel et al., 2020; Daymond et al., 2022; Hütz-Adams et al., 2022). The former scenario is characterized by poor agronomic performance (with low yields and significant harvest losses due to poor pest and disease control) and low revenue from cacao trading due to limited market access (Leandro-Muñoz et al., 2017; Mazón et al., 2018; Loukos, 2020; Zu Ermgassen et al., 2022). In contrast, the latter scenario features better agronomic performance (i.e., higher yields and fewer losses due to pests and diseases) and has better access to technical advisory and information, which, in turn, leads to greater market access and increased revenue generation (Wessel and Quist-Wessel, 2015; Loukos, 2020; Armengot et al., 2021). Nowadays, technical assistance (in both coverage and frequency) that targets small cacao farmers is missing in most agricultural sectors of LAC. Moreover, the low government budgets to train remote farmers, together with the lack of investment in on-farm research and the low internet access in rural areas, are factors that compromise capacity building and training of key actors along the cocoa value chain (Wiegel et al., 2020; World Cocoa Foundation, 2022).

Under this complex and challenging environment, sustainable cacao farming in LAC requires reality-based public policies, training and financing programs, and evidence-based cultivation models. The novel knowledge being gathered and delivered by the CacaoFIT network in LAC is the foundation for achieving profitable and sustainable cacao farming for both cultivation scenarios in the region. This study compiles knowledge and technical guidelines generated and disseminated by CacaoFIT members and highlights the key role that CacaoFIT could play in agronomy and agroforestry advocacy at the national and regional levels. The aims of this study were (1) to demonstrate the collective capacity of the CacaoFIT in testing cultivation models in LAC, (2) to gather the core research questions addressed in a subset of experimental trials, and (3) to feature the main findings and implications of the CacaoFIT for agroforestry science and practice across LAC and potentially other cacao-growing regions.

Materials and methods

The study is a synthesis made possible by the collective effort of a network of agronomists, foresters, and practitioners associated with cacao farming in either a national or regional research institution and/or a national university within the LAC regions. The methodological approach taken consisted of four steps: (1) ***Gathering general information***: We created a Google form intended to summarize the general information about each research trial. Data collected in these surveys included location and climate features, trial size (ha), age of the trial (year of evaluation), type of planting material grown, experimental design, shade canopy typology, and the overall agronomic management of the trial (Supplementary material 1). The online survey was sent to each participating institution, and one or more researchers were responsible for completing the survey for their respective cocoa plots. After all surveys were submitted, a collated datasheet was created and uploaded to a centralized repository for further analysis and open-access storage (www.erda.dk). (2) ***Featuring trials***: The third step involved the selection of a subset of five experimental trials from Honduras ($n = 1$), Colombia ($n = 2$), Bolivia ($n = 1$), and Brazil ($n = 1$). Data from these five trials were used to develop a fact sheet featuring the main findings and implications for the national cacao sector. The selection criteria of these five featured trials were: (a) willingness to share new and unpublished data, (b) a minimum size of 10 ha, (c) having recorded at least five consecutive years of data, (d) showcasing contrasting environmental and management regimes, and (e) having published at least five scientific papers from the trial. For each featured field trial, we generated descriptive statistics and graphs to show the overall performance and trends devised for five key aspects: agronomy, agroforestry, financial, environmental, and physiological measurements. Data analyzed in each featured trial include (a) crop productivity per system, (b) total system yields (cacao + goods/products), (c) accumulated incidence/severity of pests and diseases, (d) growth curve of shade/timber trees tested, (e) the total cost of establishment and management (when recorded), (f) gross/net income from several combinations of cacao + shade trees (when calculated), and (g) physiological parameter measured. (***3***) ***Description of climatic conditions and shade canopies***; following Somarriba et al. (2023), we described key elements of shade canopy variables in each featured trial, which included tree density, tree cover, species associated, tree phenology, and shade canopy management. The general climatic conditions of each experimental site were classified according to Kottek et al. (2006), and the soil type and properties were described as follows: https://soilgrids.org/. For each featured trial, we provided relevant data on the outreach actions delivered to several cacao actors at national and regional levels. (4) ***Drawing the research agenda***: We built a matrix to document the nature and extent of research agendas across the network. The matrix consists of five research domains, namely agronomy, agroforestry, environmental services, physiology features, and financial performance, with 5–7 sub-research topics each. Each person responsible for the field trial selected the list of research topics being conducted; thus, we mapped the current CacaoFIT research agenda and identified potential research gaps. We provided links to relevant publications or websites to access more detailed information on each featured trial. In this study, both current and completed cocoa trials were mapped, yet we did not document trials led by private actors in LAC. To the best of the authors' knowledge, this is the first attempt to document an entire network of cacao experimental trials across LAC.

Results

Section #1. Description of the cacaofit network in LAC

The CacaoFIT network was managed either by a public research center or university and, to a lesser extent, by non-government actors (such as research foundations or development agencies). The CacaoFIT network consisted of 25 experimental sites on 200 ha across LAC and was set up over four different ecological regions: (a) Equatorial rainforest, which is fully humid, (b) Equatorial monsoon, (c) Equatorial savannah with a dry summer, and (d) Equatorial savannah with a dry winter (Table 1). CacaoFIT was established along four altitudinal strata: low from 0 to 250 m (30% of the trials), medium from 250–500 m (45% of the trials), high from 500 to 750 m (15% of the trials), and very high ≥750 m (15% of plots). Most of the research network was established in locations where cacao farming is rarely water-limited (with the exception of the sites located in Bolivia and El Salvador). ∼70% of the experimental trials in CacaoFIT were in areas with sufficient rain (2,000–2,500 mm year), 20% of the trials were grown in humid locations (2,500–3,000 mm year), and only 10% of the plots were cultivated in dry conditions (≤1,500 mm year) (Table 1). Approximately 70% of the research trials experienced a marked dry season with 2–4 months with less than 100 mm of rain. Temperatures across the CacaoFIT trials ranged from 19°C in the South of Mexico (Chiapas) and the highlands of San Vicente, Santander, Colombia, to 37°C on the Pacific coast of El Salvador.

Experimental trials within the CacaoFIT were found to vary in size (ha), age (years of establishment), management regime

TABLE 1 Descriptors of the CacaoFIT network in terms of size (ha), establishment date, altitude, rainfall, temperature, and climatic zone.

Country*	Partners**	Area (ha)	Established	Altitude (m)	Rainfall range (mm)	Temperature range (°C)	Climatic zone+	Dry moths	Status
BOL	FiBL-El Ceibo-Farmers	5.5	2008	200–500	1,500–2,000	18–30	As	4	Ongoing
		1.25	2012	200–500	1,500–2,000	18–30	As	4	Ongoing
	FiBL-ECOTOP-Farmers	1.0	2015	200–500	1,500–2,000	18–30	As	4	Ongoing
BRA	UENF-MARS	15	2004	≤200	1,250–1,600	18–30	Af	1	Ended
	UENF-CEPLAC	5	2011	≤200	1,400–1,600	19–32	Af	1	Ended
	UENF-Instituto Sucupira	5	2019	≤200	1,900–2,100	19–31	Af	1	Ongoing
COL	CATIE-Kolfaci-Agrosavia	1.5	2018	200–500	2,500–3,000	26–32	Am	3	Ongoing
	Agrosavia	1.5	2015	200–500	2,000–2,500	20–27	Am	3	Ongoing
	U. de la Amazonia	32.0	2014	200–500	≥3,000	23–30	Am	2	Ongoing
	FEDECACAO	34.8	2000/2020	1,000–1,200	2,000–2,500	20–27	Am	3	Ongoing
CR	CATIE-GIZ-farmers	2.5	1988/1989	≤200	2,500–3,000	26–33	Af	2	Ended
	EARTH University	5.5	2000	≤200	2,500–3,000	24–33	Af	2	Ongoing
	CATIE-Kolfaci-MAG	2.0	2018/2019	≤200	2,000–2,500	24–31	Af	3	Ongoing
ECU	UTM-Manabi+ INIAP	1.5	2015	≤200	≤1,500	25–33	Am	3	Ongoing
	INIAP-CATIE	7.8	2015	≤200	≤1,500	26–34	Aw	2	Ongoing
GUA	CATIE-Kolfaci-ICTA	1.5	2018/2019	200–500	2,000–2,500	26–33	As	4	Ongoing
	Universidad de San Carlos	1.75	1990	≤200	2,000–2,500	23–32	As	3	Ended
HON	FHIA	43	1997	≤200	2,500–3,000	24–35	Af	2	Ongoing
	CATIE-Kolfaci-SAG	1.5	2018	200–500	2,500–3,000	25–34	Af	2	Ongoing
MEX	COLPOS-farmers	1.25	2012	≤200	2,000–2,500	20–33	As	4	Ongoing
	INIFAP-farmers	1.5	2012	200–500	≥3,000	19–35	Af	2	Ended
NIC	CATIE-Kolfaci-INTA	1.5	2018/2019	200–500	2,000–2,500	27–35	As	5	Ongoing
	FNF-ECOM	2.0	2020	500–700	2,000–2,500	26–34	As	5	Ongoing
PAN	GIZ-CATIE-farmers	3.5	1989/1990	≤200	2,500–3,000	24–33	Af	3	Ended
	CATIE-Kolfaci-MIDA	1.25	2018/2019	≤200	2,500–3,000	25–34	Af	3	Ongoing
PER	CATIE-Kolfaci-INIA	2.5	2018	200–500	1,500–2,000	20–33	As	3	Ongoing
	ICT-Farmers	3.3	2004	200–500	1,500–2,000	25–33	As	3	Ongoing
RD	CIRAD-CacaoForest	13.5	2017/2018	≤200	2,000–2,500	26–35	Af	4	Ongoing

(Continued)

TABLE 1 (Continued)

Country*	Partners**	Area (ha)	Established	Altitude (m)	Rainfall range (mm)	Temperature range (°C)	Climatic zone+	Dry moths	Status
	CATIE-Kolfaci-MAG	1.5	2018/2019	≤200	2,000–2,500	27–34	Af	2	Ongoing
SAL	CENTA-MAG	1.5	1992	200–500	≤1500	22–34	Aw	6	Ongoing
T & T	Cocoa Research Center	2.0	2020	≤200	1,500–2,000	23–34	Am	5	Ongoing
VEN	UNI-ANDES	2.5	2005	≤200	1,500–2,000	23–33	As	4	Ended

***Countries:** BOL, Bolivia, BRA, Brazil, COL, Colombia, CR, Costa Rica, ECU, Ecuador, GUA, Guatemala, HON, Honduras, MEX, México, NIC, Nicaragua, PAN, Panamá, PER, Perú; R.D, República Dominicana; SAL, El Salvador; T&T, Trinidad and Tobago, VEN, Venezuela. **+Climatic zones** following Kottek et al. (2006), AF, Equatorial rainforest, fully humid, Am, Equatorial monsoon, As Equatorial savannah with a dry summer and Aw, Equatorial savannah with a dry winter. Sourced from https://koeppen-geiger.vu-wien.ac.at/pdf/Paper_2006.pdf.

****Partners**: FiBL, The Research Institute of Organic Agriculture, Switzerland; El Ceibo, Central de Cooperativas El Ceibo, Alto Beni, La Paz, Bolivia; ECOTOP, an International consultancy firm and foundation specialized in the establishment and training of successional agroforestry systems across the tropics, CATIE: Centro Agronomico Tropical de Investigación y Enseñanza, Costa Rica; EARTH University, Costa Rica; GIZ, Agencia Alemana de Cooperación técnica, FHIA, Fundacion Hondurena de Investigación Agrícola, SAG: Secretaria de Agricultura de Honduras, Agrosavia: Coorporacion Colombiana de Investigacion Agropecuaria, FEDECACAO: Federación de Cacaoteros de Colombia, ICT: Instituto de Cultivo Tropicales-Perú, UTM, Universidad Tecnica de Manabi, Ecuador; INIAP: Instituto de Investigación Agropecuaria, Ecuador; ICTA: Instituto de Ciencia y Tecnología Agricolas, Guatemala; INTA: Instituto Nicaragüense de Tecnología Agropecuaria, Nicaragua; FNF: Fundación NicaFrance, Nicaragua; COLPOS: Colegio de Posgraduados de México; INIFAP: Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, México; ECOM: Grupo Ecom Trading, Nicaragua; MIDA: Ministerio de Desarrollo Agricola, Panama; INIA: Instituto Nacional de Investigacion Agraria, Perú; CIRAD: The French Agricultural Resaerch Center for International Development, France; CENTA: Centro Nacional de Tecnología Agropecuaria, El Salvador; MAG: Ministerio de Agricultura; KoLFACI: Korean-Latin Amerinca Food & Agriculture Cooperation Initiative, Republic of Korea; UNI-ANDES, The University of the Andeans, Venezuela; CRC: Cocoa Research Center, Trinidad & Tobago.

(organic vs. conventional), agroforestry design, overall research goals, and type and frequency of data collection. Trial size and age ranged from 1 to 43 ha and 3 to 25 years, respectively. Small plots were the most frequently used in research (with an average of 1.5 ha in 50% of the trials), ∼35% were medium-sized (from 2.5 to 10.0 ha), and the remaining 15% of the experimental trials were large, with plot sizes ranging from 12 to 35 ha. Small plots were common across Mesoamerica (from Mexico to Panama) and the Caribbean (the Dominican Republic and Trinidad and Tobago), whereas medium- to large-size trials were prominent in Honduras and South America, mainly in Colombia, Peru, and Brazil. More than half (55%) of the research trials documented were aged 10–12 years, ∼30% of research sites were 12–15 years old, and the remaining 20% were older (> 15 years). The two oldest and most active experimental trials were situated in humid-lowland Honduras, led by FHIA (Fundación Hondureña de Investigación Agricola) and dry-lowland El Salvador, managed by CENTA (Centro Nacional de Tecnologia Agropecuaria y Forestal). Cacao trials established by CATIE (Centro Agronómico Tropical de Investigación y Enseñanza) in Costa Rica and Panama in 1988/1989 are no longer active. Cacao experimental trials in Brazil have been established since 2000 in several locations, while most cocoa experimental trials in other South American countries (Peru, Bolivia, Venezuela, and Colombia) were established during the 2005–2010 period. The youngest experimental sites, although small, were those set up by the CATIE-KoLFACI (2018–2019) in eight countries across LAC, the Cacao Forest project (2018–2019) in the Dominican Republic, and the one recently established in 2020 at the Cocoa Research Center experimental station in Trinidad and Tobago.

Five out of the 25 experimental trials mapped in the CacaoFIT network ended their operations (for various reasons, usually linked to financial constraints). Cacao plots that tested seed-based cacao yields under leguminous shade trees (i.e., *Gliricidia sepium, Inga edulis,* and *Erythrina poeppigiana)* vs. timber trees *(e.g., Tabebuia rosea, Terminalia ivorensis,* and *Cordia alliodora*) established in the early 90s in Talamanca, Costa Rica, and Bocas del Toro, Panama, concluded data collection around 2000–2001 when financing ceased (Beer et al., 1998; Somarriba and Beer, 2011) and experimental trials were handed back to local farmers. Another timber-based cacao agroforestry systems trial set up in 2005 in Merida State and managed by the University of Los Andes, Venezuela, ended operations around 2010 due to land invasion and other political reasons (Araque et al., 2012; Jaimez et al., 2013; Mazón et al., 2018; Ávila-Lovera et al., 2016). Maintenance and data collection for the research trials led by CENTA in El Salvador and Universidad de San Carlos in Guatemala are currently facing financial constraints. The research site managed by INIFAP (Instituto Nacional de Investigación Forestal y Agropecuaria) in Mexico ended operation in 2017 after seven years of data collection due to a lack of funding. Research trials set up in 2004 by ICT (Instituto de Cultivos Tropicales) in Peru, although fully functional, ceased the data collection process in 2017 due to funding. Finally, the network of experimental trials led by UENF (Universidade Estadual do Norte Fluminense Darcy Ribeiro) and MARS and UENF and CEPLAC (Comissão Executiva do Plano da Lavoura Cacaueira) in Brazil tested a wide range of cacao + shade tree combinations operated for 10 years (2005–2015) but ended operations once collaboration agreements were over (Gama-Rodrigues et al., 2021).

Surprisingly, only three research trials in the network (FiBL in Bolivia, INIAP in Ecuador, and CRC-Trinidad and Tobago) presented unshaded plots as a control treatment.

Cacao density, planting material, shade canopies, and overall management

Fifteen out of 25 experimental trials from the CacaoFIT network are ongoing and continue doing collaborative research with national and international research institutions or universities. The CacaoFIT network has tested a wide range of planting densities and genetic material. Approximately 150 distinct cacao genotypes/clones were assessed in a mixture of 8–10 clones per plot. Across the network, planting density was classified as low ($<$625 plants ha^{-1}) in 20% of cases, medium (between 625 and 833 plants ha^{-1}) in another 20%, high (1,111 plants ha^{-1}) in another 45%, and very high ($\geq$1,300 plants ha^{-1}) in the remaining trials (Table 2). Most research trials were managed conventionally (i.e., 55%), defined by the use of synthetic inputs, fertilizers, mechanical weeding, etc. Meanwhile, 20% were managed via organic practices defined by the absence of agrochemicals aside from the application of bioproducts and manual weeding practices. The remaining 25% of trials utilized both conventional and organic management for comparison purposes. Additionally, most research trials (80%) performed soil analysis at the beginning of the experiment and continue to do so every two to three years as a means of monitoring changes in physical and chemical soil properties, as well as the effects on enhancing soil biota.

Most trials (ca. 60%) managed both well-known international clones and national cultivars from selection programs; the remaining 30% grew locally selected elite trees, and only 10% grew seed-based cocoa plantations for comparison purposes (mainly in Bolivia, El Salvador, and Peru). Completed trials run by CATIE in Costa Rica and Panama, as well as managing both seed-based cacao plants from controlled pollination and a set of international clones (Somarriba and Beer, 2011). Interestingly, the experimental trial set up by ECOM and Fundación NicaFrance in Nicaragua is currently testing plants derived from somatic embryogenesis. Most experimental trials (90%) were rain-fed, and only five (the ones located along the dry Pacific coast of Ecuador and El Salvador) were irrigated. Mixed shade canopies were dominant across research trials (70%), while timber-based vs. leguminous shade trees were also tested in 20% of the trials (mainly in Colombia and Central America). Timber-based agroforestry systems were dominant in Honduras, while simple shade canopies or full-sun cacao within the CacaoFIT were less common. The research trials set up by UENF + MARS + CEPLAC tested a wide range of cacao-shade tree combinations, including mixed shade, leguminous trees (*Erythrina* sp., *G. sepium*), cacao + coffee (*Coffee canephora*) + teak (*Tectona grandis*), cacao + rubber trees (*Hevea brasilensis*), and other mixtures of cacao with native fruit trees (*Anona muricata*, *Spondias mombin*), timber (*Schizolobium amazonicum, Tabebuia heptaphylla, C. alliodora, Tabebuia heptaphyllam, Bagassa guianensis, C. guianensis*), and palm trees such as Acai (*Euterpe oleracea*), peach palm (*Bactrias gasipaes*), coconut (*Coconut nuficera*), and Brasil nut (*Bertholetia excelsa*). For a full description of these diverse shade canopies, see Gama-Rodrigues et al. (2021).

Nature of the research being conducted across the CacaoFIT network

The diversity and depth of research domains conducted across the CacaoFIT network varied greatly. Agronomy and agroforestry themes dominated the research agenda of all experimental sites. Regarding agronomy, cacao plant growth and vigor, accumulated yields, and the incidence of pests and diseases were the most common research topics. More complex topics, such as the dynamics of pod production and the effects of pruning (frequency and intensity) on yields, had been recently conducted by a handful of research trials. Regarding agroforestry, the topics documented by nearly 75% of the experimental trials were shade tree growth, generation of goods/products from associated trees (annual crops, timber, fruits, firewood, etc.), and the assessment of canopy cover over time (Figure 1). Shading factors and tree phenology (foliage dynamics) were seldom assessed within the CacaoFIT network (Saj et al., 2013; Magne et al., 2014; Schneider et al., 2017; Armengot et al., 2021; Sauvadet et al., 2021).

Regarding the set of environmental/ecosystem services, most research trials (65%) have documented carbon stocks, sequestration rates, and nutrient cycling, whereas topics such as the abundance/habitat of pollinators, local biodiversity, and soil/micro and macro fauna were assessed to a lesser extent. Other research topics, such as rainfall partitioning and litterfall/decomposition rate, were overlooked across CacaoFIT; so far, the trials led by FiBL in Bolivia, Agrosavia in Colombia, and CEPLAC in Brazil were the only ones that were researched and published on these topics. Climate variables (precipitation, temperature, wind speed, and relative humidity) for most research trials (80%) were gathered by in-site or nearby weather stations, while microclimate variables were rarely measured locally. Again, the research trail from FiBL in Bolivia is leading the way concerning microclimate-shade management-yield relationships.

Concerning the physiological features of cacao plants, namely leaf area index, sap flow, chlorophyll fluorescence, gas exchange (CO_2 assimilation, transpiration, and leaf conductance), and water relationships (leaf water potential and osmotic adjustment), only $\sim$40% of the research trials within CacaoFIT have conducted this set of studies. Physiological measurements were commonly taken by experimental trials in Colombia, Bolivia, and Venezuela, which produced several articles in both English and Spanish. Physiology research topics were almost absent in Mesoamerica and the Caribbean, presumably due to a lack of equipment, instruments, and skilled staff (Ramon E. Jaimez, Universidad Tecnica de Manabi, Ecuador, and personal communication). Finally, regarding the financial performance of cacao farming, annual profitability, and cost/benefit analysis were the most common key financial indicators tested in $\sim$70% of the CacaoFIT network. Except for the study conducted by Ramirez et al. (2001), risk analysis and long-term financial modeling are not fully developed themes. Novel topics such as labor, energy demand, food safety, and lifecycle assessments were assessed only by the trial in Bolivia (Armengot

TABLE 2 Management of the CacaoFIT network, including planting density, the origin of planting material, farm systems, and type of shade canopy.

Country*	Partners**	Cacao Density (plants/ha)	Planting material (clones/cultivars)	Soil test	Farm system	Irrigated (yes/no)	Shade canopy
BOL	FiBL-El Ceibo-Farmers	625	International/local selection	Yes	Organic and Conventional	No	Mixed shade, Successional + Full sun
	FiBL-ECOTOP-Farmers	625	International/local selection	Yes	Organic and Conventional	No	Mixed shade, Successional + Full sun
BRA	UENF-MARS	700–2,500	CEPLAC clones	Yes	Conventional	No	Diversified shade + Leguminous trees
	UENF-CEPLAC	1,111	CEPLAC clones	Yes	Conventional	No	Diversified shade + Timber trees
	UENF-Instituto Sucupira	1,250	CEPLAC clones	Yes	Conventional	No	Leguminous trees + Native fruit trees
COL	CATIE-Kolfaci-Agrosavia	1,111	National clones	Yes	Organic and Conventional	Yes/No	Timber trees in simple/double lines
	AGROSAVIA	1,111	National clones/local selection	Yes	Conventional	No	Timber shade trees
	U. de la Amazonia	833	International/national clones	Yes	Conventional	No	Timber shade trees
	FEDECACAO	1,111	National/local clones	No	Organic and Conventional	No	Timber shade trees
CR	CATIE-GIZ-farmers	833	Hybrids, seed-based plants	No	Conventional	No	Leguminous + timber
	EARTH University	1,111	Internacional/CATIE clones	Yes	Organic	No	Leguminous shade + Mussa spp.
	CATIE-Kolfaci-MAG	1,290	CATIE clones	Yes	Organic and Conventional	No	Mixed shade+ trees in the borders.
ECU	UTM-Manabi + CATIE	1,111	National clones/local selection	Yes	Conventional	Yes	Mixed shade/Full sun
	INIAP-Amazonia + CATIE	1,111	EET-103 + EET-96/Local selection	Yes	Organic	No	Timber + Palms + Fruit trees
GUA	CATIE-Kolfaci-DICTA	1,290	CATIE clones	Yes	Organic and Conventional	No	Mixed shade+ trees in the borders
	Univ. San Carlos	888	Hybrids, seed-based plants	No	Organic	No	Mixed shade
HON	FHIA	1,111	International clones	Yes	Conventional	No	Timber shade
	CATIE-Kolfaci-SAG	1,290	International/CATIE clones	No	Organic	No	Mixed shade

(Continued)

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TABLE 2 (Continued)

Country*	Partners**	Cacao Density (plants/ha)	Planting material (clones/cultivars)	Soil test	Farm system	Irrigated (yes/no)	Shade canopy
MEX	COLPOS-farmers	1,111	National and international + criollo selected seeds	Yes	Conventional	No	Mixed shade
	INIFAP-farmers	833	Criollo selected seed and elite trees	No	Organic	No	Mixed shaded + Mussa.
NIC	CATIE-Kolfaci-INTA	1,290	CATIE clones	Yes	Organic and Conventional	No	Mixed shade+ trees in the borders.
	FNF-ECOM	1,111	Plants from somatic embryogenesis	Yes	Conventional	No	Mixed shade + Mussa spp
PAN	GIZ-CATIE-farmers	833	Hybrids, seed-based plants	No	Conventional	No	Leguminous + timber
	CATIE-Kolfaci-MIDA	1,290	CATIE clones	Yes	Organic and Conventional	No	Mixed shade+ trees in the borders.
PERU	CATIE-Kolfaci-INIA	1,290	National clones	Yes	Organic and Conventional	No	Mixed shade/Trees in the borders.
	ICT-Farmers	833	National/local clones	Yes	Organic and Conventional	No	Leguminous shade + Mussa spp.
RD	CIRAD-CacaoForest	625	Selected trees, IDIAF cultivars, and international clones	Yes	Organic	No	Diversified shade.
	CATIE-Kolfaci-MAG	1,290	National clones/local clones	Yes	Organic	No	Mixed shade+ trees in the borders
SAL	CENTA-MAG	833	Selected elite criollo trees/local seeds	Yes	Conventional	Yes	Leguminous trees
T&T	Cocoa Research Center	1,500	Local clones/selected elite trees	Yes	Conventional	Yes	Leguminous shade vs. No shade/full sun
VEN	UNI-ANDES	833	Criollo cultivars: Porcelana, Merideño, Guasare, Lobasare.	Yes	Conventional	Yes	Timber + Leguminous

Countries: *BOL, Bolivia; BRA, Brasil; COL, Colombia, C.R, Costa Rica, ECU, Ecuador, GUA, Guatemala, HON, Honduras, MEX, México, NIC, Nicaragua, PAN, Panamá, PER, Perú; RD, República Dominicana; SAL, El Salvador; T&T, Trinidad and Tobago; VEN, Venezuela.

Partners: **FiBL, The Research Institute of Organic Agriculture, Switzerland; El Ceibo, Central de Cooperativas El Ceibo, Alto Beni, La Paz, Bolivia; ECOTOP, an International consultancy firm and foundation specialized in the establishment and training of successional agroforestry systems across the tropics, CATIE: Centro Agronómico Tropical de Investigación y Enseñanza, Costa Rica; EARTH University, Costa Rica; GIZ, Agencia Alemana de cooperación técnica; FHIA, Fundación Hondureña de Investigación Agrícola, SAG: Secretaria de Agricultura de Honduras, Agrosavia: Corporación Colombiana de Investigación Agropecuaria, FEDECACAO: Federación de Cacaoteros de Colombia, ICT: Instituto de Cultivo Tropicales-Perú, UTM, Universidad Técnica de Manabí, Ecuador; INIAP: Instituto de Investigación Agropecuaria, Ecuador; ICTA: Instituto de Ciencia y Tecnología Agrícolas, Guatemala; INTA: Instituto Nicaragüense de Tecnología Agropecuaria, Nicaragua; FNF: Fundación NicaFrance, Nicaragua; COLPOS: Colegio de Posgraduados de México; INIFAP: Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias, México; ECOM: Grupo Ecom Trading, Nicaragua; MIDA: Ministerio de Desarrollo Agrícola, Panamá; INIA: Instituto Nacional de Investigación Agraria, Perú; CIRAD: The French Agricultural Resaerch Center for International Development, France; CENTA: Centro Nacional de Tecnología Agropecuaria, El Salvador; MAG: Ministerio de Agricultura; KoLFACI: Korean-Latin Amerinca Food & AGriculture Cooperation Initiative, Republic of Korea; UNI-ANDES, The University of the Andeans, Venezuela; CRC: Cocoa Research Center, Trinidad & Tobago.

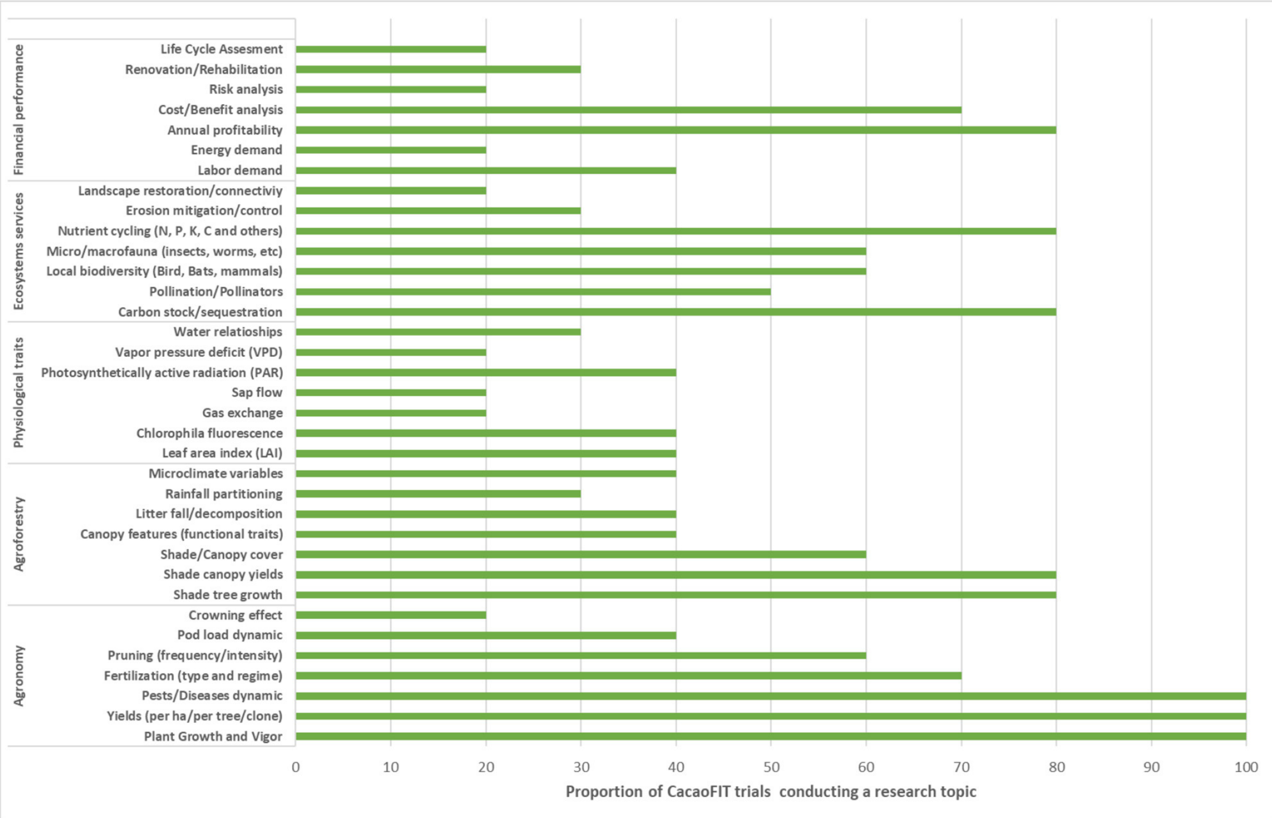

FIGURE 1
Diversity and depth of research domains and topics being conducted across the CacaoFIT network.

et al., 2016; Pérez-Neira et al., 2020, 2023). Establishment and maintenance costs of both conventional and organic management were researched to a lesser extent. In summary, research gaps across the CacaoFIT network were evident and deserved attention.

Section #2. Featured cacao field trials from the CacaoFIT network

Featured trial #1. Native timber-based cacao agroforestry systems in lowland Honduras

In 1986, framed in the cacao and agroforestry research program, FHIA established a network of 36 experimental plots (43 ha in total, ranging in size from 0.5 to 1.5 ha per plot) that combined 12–15 cacao varieties (density=1100 plants ha^{-1}) with 36 timber shade species (29 native species and seven exotic species) aimed at testing the agronomic and agroforestry performance of cacao timber-based agroforestry systems and delivering technical guidelines for cacao farming in humid-lowland Honduras (Figure 2). For over two decades, FHIA and partners have registered monthly data on cocoa yields and by-crops production, costs of agronomic inputs, income from harvested products, and the incidence of pests and diseases. Tree growth parameters (diameter and height) and shade tree phenology features (crown width and shading factors) were recorded annually. Research outcomes generated from this research trial were:

Agronomy outcomes

- The cacao production peak is exhibited between 13–17 years after planting, and attainable yields were in the range of 685 to 2250 kg ha^{-1} year^{-1}, 3X higher than the national average productivity (Figure 3). This finding confirmed that timber-based cacao agroforestry systems produce satisfactory yields comparable to that of leguminous shade trees.
- Over 20 years, frosty rot pot (*Moniliophtora roreri*) + black pod (*Phytohtora palmivora*) incidence ranged from 5 to 18%, demonstrating that the timely removal of infected pods is effective in reducing yield losses (Figure 3). More details are in Ramírez-Argueta et al., 2022. Mineral fertilization (15-15-15, 12 g/plant) applied annually in three equal doses and lime amendments applied yearly at a single dose of 0.5 t ha^{-1} year^{-1} is key to sustaining yields.
- The set of best practices for sustainable cacao yield over time devised from this trial was: (a) cacao pruning must be done twice a year following a 2.5 m plant high threshold, (b) weekly removal of diseased pots during production peaks and fortnightly during low harvest periods, and (c) fertilization and weeding must be performed at least three times a year.

Agroforestry outcomes

- Cacao yields were greater when tree cover and timber basal area were below 40% and 12 m^2, respectively. In line with the competitive allocation of the basal area model suggested by

FIGURE 2
Distribution of the 43 ha of timber-based cacao agroforestry systems across the CEDEC-JAS experimental site in La Masica, Atlántida, Honduras. Photo: FHIA 2020.

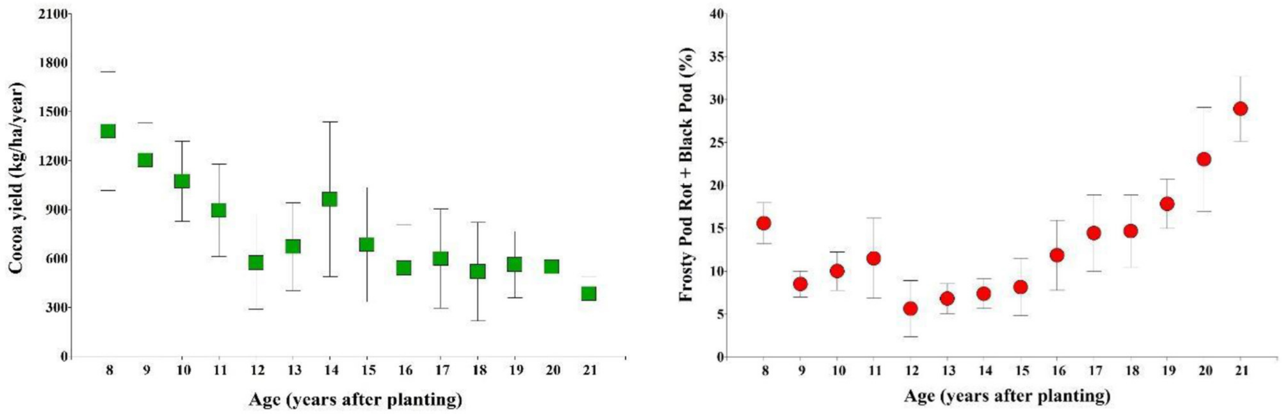

FIGURE 3
Cacao yield (green squares) and incidence of frosty pod rot + black pod (red dots) curves over 20 years in CEDEC-JAS, FHIA, La Masica, Atlantida, Honduras. Mean values and confidence interval across 12 plots.

Somarriba and López (2018a), this is key for the design and management of shaded cacao plots.

- The growth rates of 12 native timber species were promising (Ramírez-Argueta et al., 2022); the mean diameter was 2.4 cm year^{-1}, and the average tree height was 1 m year^{-1} (Figure 4). Most species reached the minimum harvesting diameter (30 cm) at the age of 13–15 years and gained, on average, 4.25 m^3 ha^{-1} year^{-1}. This finding confirmed that native timber species were suitable for cacao cultivation and that timber harvest at shorter timelines was feasible.
- *Dalbergia glomerata*, a native timber species, displayed an inverted phenology pattern: it loses foliage during the rainy season and retains it during the dry season. This unique phenological behavior is of great interest for cacao cultivation in areas with marked dry seasons, suggesting that the species could be incorporated into resilient agroforestry models.

Environmental/Ecosystem Services: Data has not been recorded/published yet.

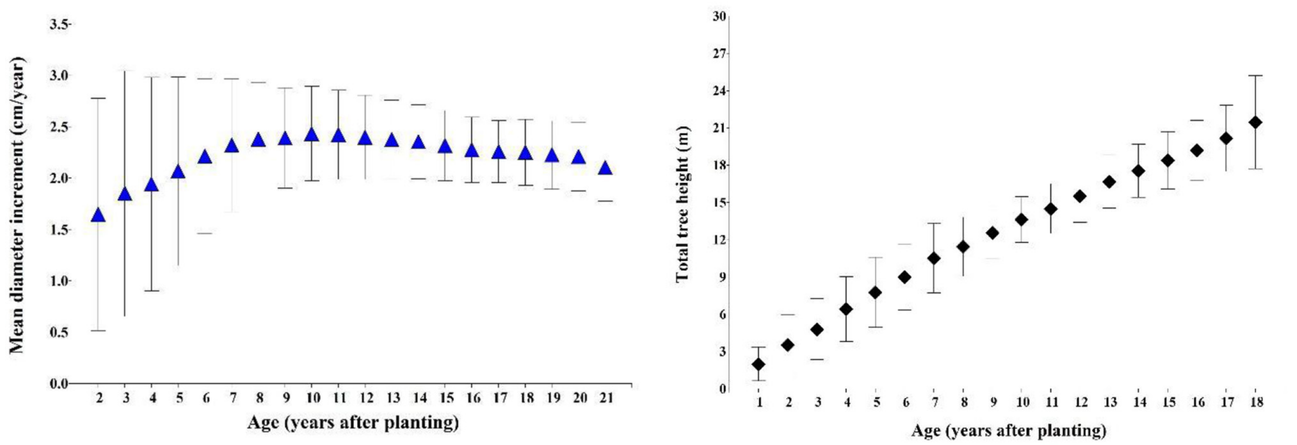

FIGURE 4
Growth rates of diameter (blue triangles) and total height (black diamonds) curves of 12 timber species in CEDEC-JAS, FHIA, La Masica, Atlantida, Honduras. Mean values and confidence intervals are shown.

Financial outcomes

- Total revenues registered were determined by the proportion of income provided by each component of the shaded system: cacao (45%), timber trees (45%), and plantain + *G. sepium* (10%). Thinning of timber trees might provide additional funds to farmers.
- After 22 years, farmers' incomes from timber-shaded cacao plots were in the range of U\$1775 ha^{-1} year^{-1} to U\$3300 ha^{-1} year^{-1}, depending on cacao and timber local prices.
- Establishment costs ranged from U\$2,500–\$\$3,000 ha^{-1}, while maintenance costs varied from U\$700-U\$1000 ha^{-1} year^{-1}. Most cacao plots reached a positive economic balance four years (between five and six) after planting when incomes exceeded annual management costs.

Physiological features: Data were not recorded/provided.

Outreach: Over the last decade (2010–2020), a total of 7,993 people from 15 different countries have been trained by the CEDES-JAS staff, including 4,160 farmers, 1,612 students, and 2,220 technicians. Several planting designs for cacao cultivars have been provided to development projects, private investors, and national cacao programs. FHIA is an active member of the Cocoa Board in Honduras, providing technical advocacy and conducting collaborative applied research. Finally, annual technical reports have been published during the last decade (2009–2021) and are available at http://www.fhia.org.hn/html/Programa_de_Cacao_y_Agroforesteria.html.

Featured trial #2. Long-term systems comparison (SysCom) in the Sara Ana center for research and capacity development, Alto Beni, La Paz, Bolivia

Between 2008 and 2010, FiBL, in partnership with El Ceibo and ECOTOP, set up a network of seven ha of research plots aimed at comparing agroforestry systems and monocultures under both organic and conventional management. A fifth treatment included successional or dynamic agroforestry systems with no external inputs. Gross research plot size was 48 m × 48 m (2,304 m^2), while net plots were 24 m × 24 m (576 m^2). For all treatments, cacao and plantains were planted at a low density (625 ha^{-1}) (Figure 5). Since 2009, FiBL and partners have regularly registered data on yields of cocoa and by-crops, labor time, costs of agronomic inputs and income from harvested products/goods, tree growth, pests, and diseases, as well as the phenology of cacao trees, soil fertility, and shade canopy management. Research outcomes derived from the SysCom trial were:

Agronomy outcomes

- In monocultures, cocoa yields were ~15% higher in conventional systems compared to organic ones (data from 2015 to 2020). This is likely due to the suboptimal amount and timing of nutrient delivery from compost, as well as nutrient competition with cover crops in organic systems. These findings suggest a more consistent organic fertilization plan.
- In agroforestry systems, cocoa yields were equal in organically and conventionally managed systems; however, yields were ~40% lower than in monocultures. This is due to the slower growth and the limited light availability of cacao plants.
- Cocoa yields in all systems studied were clearly above the yields of many farmers in the region and can be increased up to 6-fold with the choice of locally adapted varieties compared to internationally known varieties (Niether et al., 2017) (Figure 6).
- With the application of good agricultural practices (e.g., frequent harvesting, removing infected cocoa pods, and regular pruning of cacao and shade trees), all cacao production systems experienced low total pest and disease incidence (Armengot et al., 2020).

Agroforestry outcomes

- Agroforestry systems have higher total system yields of all harvested products/goods (cocoa, plantains, bananas, other fruits/tuber crops) compared to monocultures, resulting in a substantially higher nutritional output compared to monocultures (Niether et al., 2020; Sauvadet et al., 2020; Rüegg et al., 2024, in preparation).

FIGURE 5
An aerial image of the SysCom long-term trial, where the five production systems are represented in different colors: conventional monoculture (CM, yellow), organic monoculture (OM, dark blue), conventional agroforestry (CA, light blue), organic agroforestry (OA, white), and successional agroforestry (SA, red) (photo by Marco Picucci, FiBL, https://www.fibl.org/en).

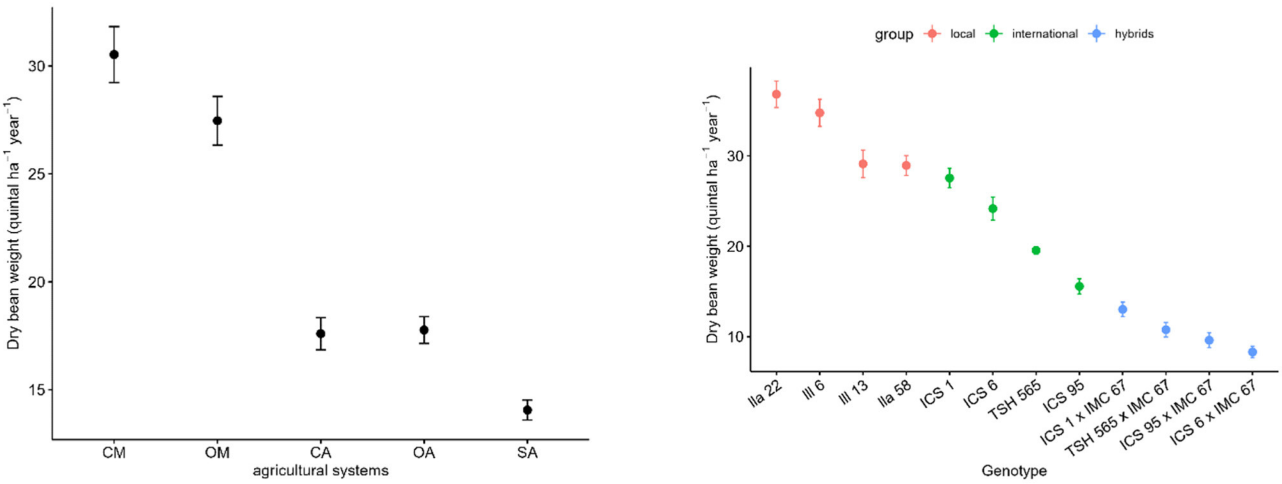

FIGURE 6
Mean cacao yields between 2018 and 2022 for the five agricultural systems **(left)** and genotype group regardless **(right)**. Bars represent standard errors. CM, conventional monoculture; OM, organic monoculture; CA, conventional agroforestry; OA, organic agroforestry; SA, successional agroforestry (Source: FiBL, 2023). Note: 1 quintal = 45 kg or 100 pounds.

- Although the fine roots from cacao and agroforestry trees overlapped and thus might compete, the roots of agroforestry trees explore deeper layers of the soil, with this complementary use of the soil leading to higher system yields and higher biomass production in agroforestry systems as compared to monocultures (Niether et al., 2019).
- Shade cover is dynamic; hence, its management across agricultural systems is key to maintaining satisfactory crop yields and reducing losses due to pest and disease pressure. In this trial, the recommended level of shade cover for acceptable cacao yields was 40%.

Environmental outcomes

- In cacao, conventional and monoculture systems use more energy from non-renewable resources (e.g., fuel and electricity) compared to organic and agroforestry systems (Pérez-Neira et al., 2020). Increasing the complexity of the system, agroforestry vs. monocultures resulted in higher biodiversity and conserved rare and native plant species (Marconi and Armengot, 2020).
- Agroforestry systems sequester up to three times more carbon in their biomass than monocultures (Schneider et al., 2017). At the same time, they buffer the negative effects of temperature peaks and heavy rainfall or drought (Niether et al., 2018). This microclimatic effect is also influenced by the pruning of shade trees (Niether et al., 2018).
- In agroforestry systems, regular pruning of trees, many of which are leguminous, enhances carbon and nitrogen cycling in the soil-plant system (Schneider et al., 2017).

Physiological features: Data has not been provided/published yet.

Outreach: The SuyCom trial supports numerous research and extension activities. To date, over 25 articles have been published in international journals, and ∼45 students from Bolivia and elsewhere completed their academic theses based on the work done in the trial. Sara Ana also offers courses on agroforestry design and management to dozens of farmers and technicians from Bolivia and Latin America. Around 1,000 individuals visit the site each year.

Featured trial #3. Agroforestry models for fine-flavor cacao and value timber in Colombia-Agrosavia

In 2008, Agrosavia established a research trial of 1.5 ha in two localities aimed at comparing the performance of international and local cacao clones shaded by native and exotic timber species. The trial was established under a randomized complete block design with nine treatments (nine cocoa genotypes) in a factorial design with three repetitions. Cacao was planted under abarco (*Cariniana piryformis*) and caucho (*Hevea brasiliensis*) trees in site #1 and under *C piryformis* and teca (*Tectona grandis*) in site #2. The selection of shade tree species responded to local preferences and market potential. Dasometric variables were measured for shade trees, cacao yields, and the incidence of monilia (*Moniliophthora roreri*) by cacao genotype. Data have been recorded for over 10 years per agroforestry combination, which has yielded several scientific and technical publications. Research outcomes devised from the two medium-term trials were:

Agronomy outcomes

- Cacao clones shaded by *C. piryformis* that showed the highest yield were TCS-19 and TCS-13 with 1.8 t ha^{-1} and 1.6 t ha^{-1} dry beans, respectively. Registered yields here were comparable to those of nearby commercial farms. The yields of the other seven cacao clones under *H. brasiliensis* and *T. grandis* were similar among them (0.5 to 0.75 t ha^{-1}) (Figure 7).
- The productivity of cacao genotypes registered in both study sites was 3x higher than the average national yield reported by FEDECACAO (2020).
- Overall, the lowest incidence of monilia (15% on average) was registered in cacao genotypes growing under *C. piryformis*; the least affected cacao genotypes were TCS-19 and TCS-13, with 5% and 8% affectation, respectively (Figure 8). The incidence of monilia registered under the remaining two shade species was similar and ranged from 15% to 25%.
- Cacao pruning twice a year, fortnightly removal of infected pods, and regular fertilization (450 g of N, P and K) $plant^{-1}$ $year^{-1}$ are key to sustaining cacao yields over time.

Agroforestry outcomes

- After 10 years, tree height growth rates were similar among the timber species evaluated. Nevertheless, *H. brasiliensis* grew taller (15.4 m), followed by *T. grandis* (14.5 m) and *C. piryformis* (14.1 m).
- The diameter growth rates of the three species were also similar. After a decade, *C. piryformis* reached 22.5 cm, followed by *T. grandis* (19.8 cm) and *H. brasiliensis* (19.3 cm) (Figure 9).
- Linear plating arrangements in both, instead of squared planting design, have proven to be effective in controlling wind speed, thereby mitigating monilia dispersion across the plantation.

Environmental outcomes

- The contributions of shade tree species to nutrient cycling differed between sites. In the Rionegro site, *C. pyriformis* trees provided 2,484 kg ha^{-1} yr^{-1}, cocoa trees deposited 1,730 kg ha^{-1} $yr^{-1,}$ and teak trees incorporated 1,306 kg ha^{-1} yr^{-1} as pruning residuals. The highest nutrient contribution was made by the cocoa-abarco shaded system (Rojas-Molina et al., 2017; Jaimes-Suárez et al., 2022).
- The carbon stocks of these agroforestry systems also differed between sites. Higher C storage was found in TCS-13 associated with *C. pyriformis* compared to TCS-19 grown under *T. superba*. Cocoa TCS01 under the shade tree *C. pyriformis* might have reduced carbon loss due to decreased respiration in non-photosynthesizing tissues (Carvalho et al., 2023).

Physiological features

- The photosynthetic rates differed among clones, shade tree species, and seasons. In the El Carmen site, cacao clones showed lower photosynthetic efficiency (4.75 $\mu mol\ m^{-2}\ s^{-1}$, 4.57 $\mu mol\ m^{-2}\ s^{-1}$) than those growing in the Rionegro site. In Rionegro, cacao genotypes shaded by abarco trees registered a statistically higher photosynthetic efficiency rate (5.39 $\mu mol\ m^{-2}\ s^{-1}$) as compared to that of cacao clones shaded by teak trees (5.04 $\mu mol\ m^{-2}\ s^{-1}$).
- At both sites and across clones, photosynthetic efficiency rates were consistently lower during the dry season compared to the rainy season. Clones with higher photosynthetic rates were TCS 19, SCC 53, SCC 83, and TCS 19 with 5.63, 5.09, 5.3, and 4.95 $\mu mol\ m^{-2}\ s^{-1}$, respectively. For more details, review the work by Agudelo-Castañeda et al. (2018).

FIGURE 7
Frontal view of the cacao + *Cariniana piryformis* (Abarco) agroforestry systems in El Carmen de Chucurí, La Suiza, Santander, Colombia (Photo: Montealegre Bustos et al., 2021).

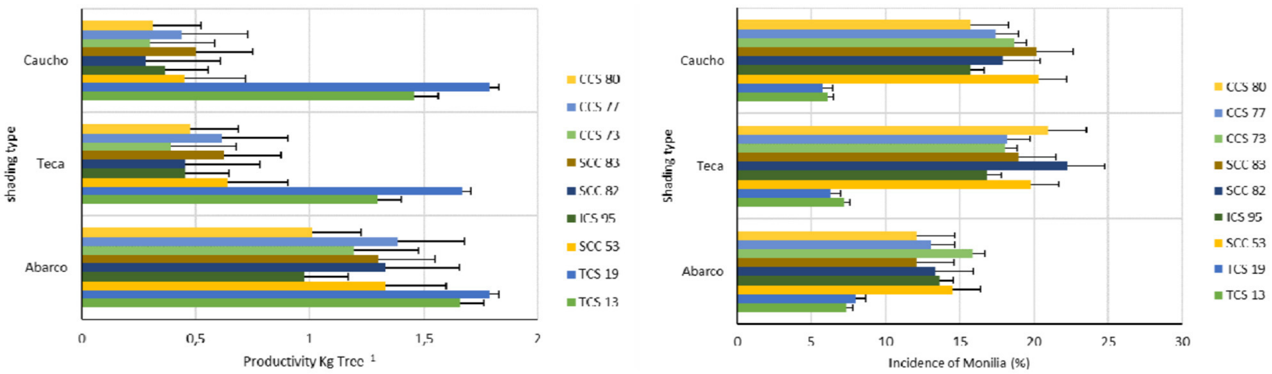

FIGURE 8
Productivity (kg tree^{-1}) and incidence of *M. roreri* of nine cocoa clones grown under timber shade species in the research site, Santander, Colombia (from Agudelo-Castañeda et al., 2023).

- Remarkably, the association between *C. pyriformis* and the TCS01 cocoa genotype rendered higher leaf-level water use efficiency and greater total carbon storage compared to the combination of *T. superba* with TCS19. For more information, see Leite Carvalho et al. (2023).

Financial outcomes: No published yet. See Montealegre Bustos et al. (2021).

Outreach: Between 2017 and 2022, Agrosavia trained ~6,000 people (90% farmers, 6% academics and students from national universities and technical colleges, and 3% extensionists. Training is usually delivered via workshops (42%), professional courses (30%), field discovery days (18%), and other means (10%). Agrosavia is part of the National Agricultural Science and Technology System, which defines policies in the sector and serves to leverage research resources. All scientific and technical publications can be found at https://www.agrosavia.co/biblioteca.

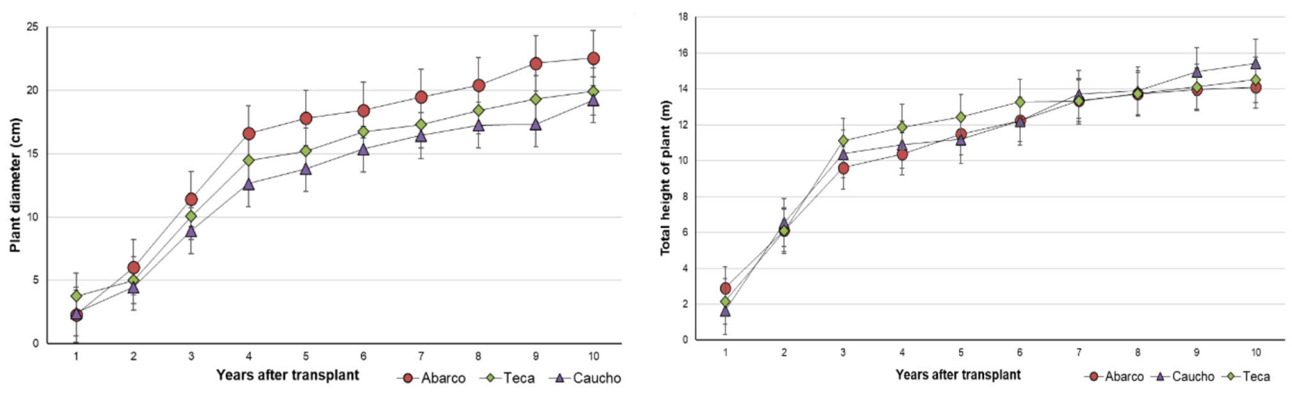

FIGURE 9
Truck diameter (DBH-cm) and total height (m) registered for Abarco (*C. piryformis)*, Teca (*T. grandis*), and Caucho (*H. brasiliensis*) over a 10-year period, Santander, Colombia.

Featured trial #4. Yield and physiological performance of cocoa clones under different agroforestry systems in the Colombian Amazon

In 2014, the University of the Amazonia set up the Macagual Amazon Research Center, Caquetá department, in western Amazonia, comprising 32 ha of cacao-shade tree combinations (AFS) under a randomized complete block design with five replications. In each block, treatments were arranged in strip plots. One strip contained the four AFS, while in the strip perpendicular to the AFS, the clones were randomly planted. The average plot size was 1.5 ha, shaded by several species, including Huito (*Genipa americana*), Caracoli (*Anacardium excelsum)*, Abarco (*Cariniana pyriformis)*, and Capiron de Vega (*Calycophyllum spruceanum*). In each block, shade trees were planted at 12 x 12 (70 trees ha^{-1}), and cacao was planted in a north-south direction at 3.5 × 3.5 m (816 plants ha^{-1}). Shade tree species were selected by local farmers based on leaf traits (leaf size, N fixation), canopy traits (crown size and phenology,) and value. The overall goal of the long-term trial is to evaluate the adaptability of both national and international clones shaded by different AFS and under Amazonian conditions. Data collection was carried out from 2018 to 2022, and key research outcomes from this trial were as follows:

Agronomy outcomes

- Differences have been found regarding agronomic variables at the genotype level; clones CCN-51, FEAR-5, FEC-2, and FGI-4 registered the highest values of pod and seed index.
- During the first two years of production (2018–2020), clones FEAR-5, FGI-4, and FLE-3 yielded ≥25 pods $tree^{-1}$ $year^{-1}$ and clones FEC-2 and EET-8 loaded ≤10 pods per $tree^{-1}$ year $^{-1}$.
- Total yield per clone ranged between 0.40 and 2.40 kg/year/tree. Clones CCN-51, FGI-4, LUK-40, and ICS-60 showed the highest value, while FTA-2, ICS-39, EET08, and LUK-50 were the lowest-yielding clones (Figure 10).
- The incidences of diseases varied widely across clones; monilia affectation ranged between 0 and 80%, while phytophthora ranged between 0 and 70%. The clones less affected by both diseases were FSA-13, TSH-565, ICS 1, IMC 67, ICS 95, and FSA-12 (Figure 11).

Agroforestry outcomes

- Regarding the effects of the agroforestry system on yields, cacao clones growing under *Anacardium excelsum* and *Genipa americana* showed the highest yield (Figure 12).
- Eight years after planting, shade species reached a diameter between 5.6 and 23.4, crown area varied from 3.0 to 66.5 m^2, the total tree height was in the range of 4.2–9.2 m, and commercial tree height was from 2.3 to 4.4 m.
- Above-ground carbon accumulation in the control plot (full sun cacao) reached 6.4 tons compared to 16.7 tons on shaded plots. Soil carbon at 0–10 cm depth reached 24.3 g kg^{-1} in cocoa plots shaded by *G. americana* trees, compared to 18.9 g kg^{-1} in full-sun cocoa plots.
- The contribution of litterfall in shaded plots reached 6.5 Mg ha^{-1}, and the decomposition rate of 50% of the litterfall ranged from 27 to 65 days.

Physiological outcomes

- The performance of the photosynthetic apparatus under full-sun conditions was higher for clone ICS-95, which showed the highest values of Vc_{max} and J_{max} (Suárez Salazar et al., 2021).
- Under the Amazonian region, which is characterized by high cloudiness, the rate of net carbon assimilation, RuBisCO carboxylation, and RuBP regeneration rates were higher in cacao trees under full sun compared to those in shaded conditions. (Suárez Salazar et al., 2018b).
- The microclimatic variables in shaded conditions are significantly modified compared to full-sun cocoa plots (Suárez Salazar et al., 2021), which, in turn, affects sap flow. The maximum sap flow average values were 0.27 ± 0.03 L h^{-1} at daytime and 0.0300 ± 0.0023 L h^{-1} at night.

Environmental outcomes

- In this site, cocoa agroforestry systems were planted on degraded pasture areas, and after three

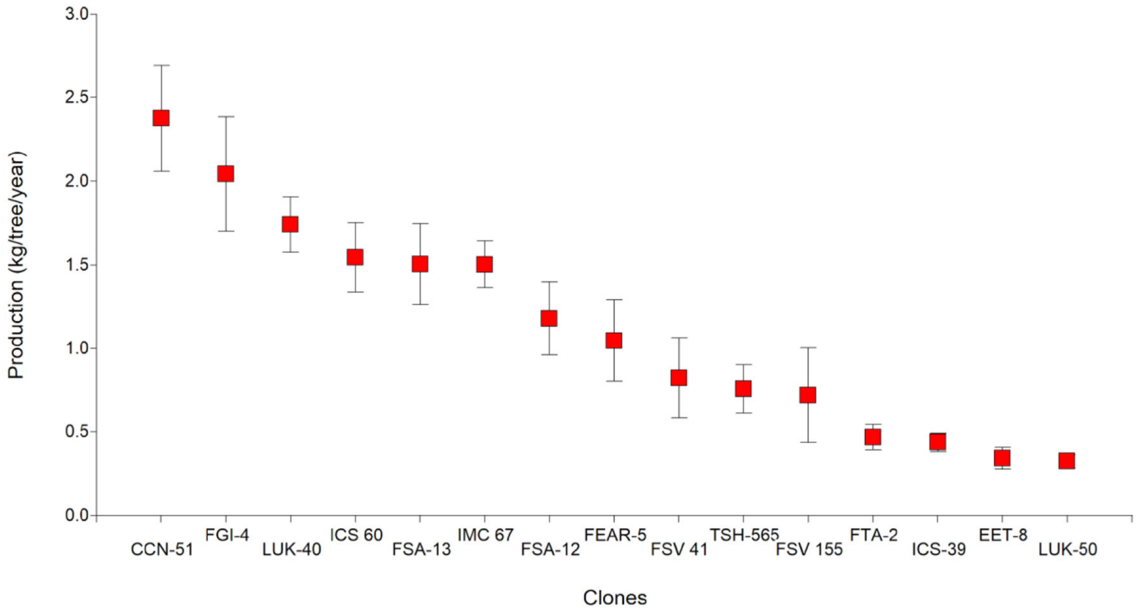

FIGURE 10
Early yield (kg tree^{-1} year^{-1}) of 15 cacao clones being tested under different agroforestry systems in the CIMAZ experimental site, Amazonia, Colombia.

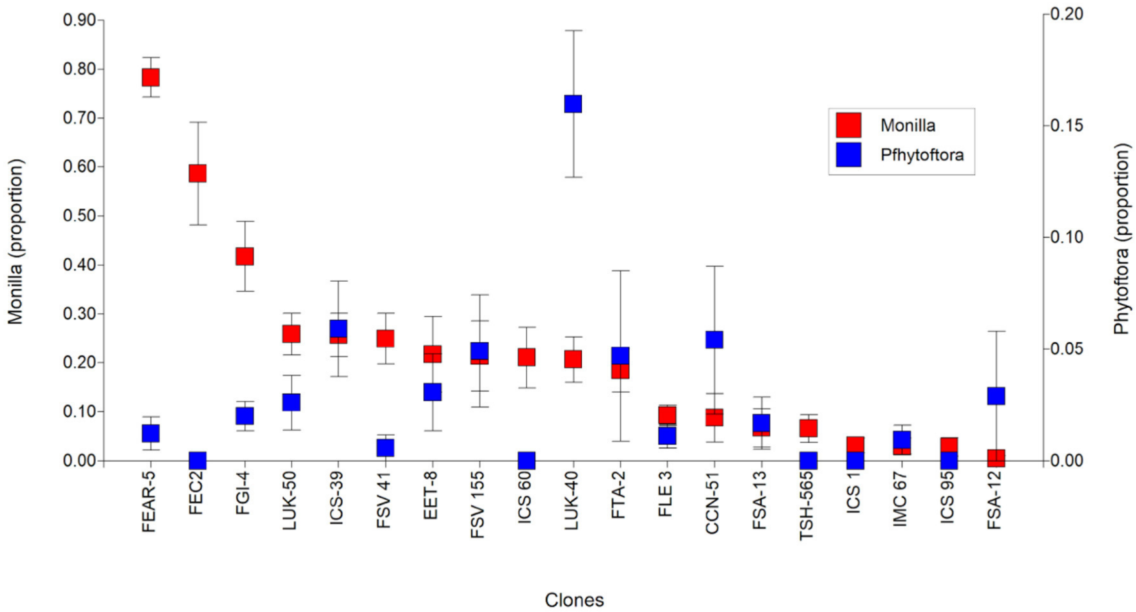

FIGURE 11
Proportion of pods infected by frosty pod rot and black pod among 15 clones being tested in the CIMAZ experimental site, Amazonia, Colombia.

years of evaluation, the GISQ increased from 0.21 to 0.59.

- Macrofauna populations of the Isoptera order increased notably, which, in turn, enhanced the amount of soil aggregates and therefore carbon stability.
- Regarding soil carbon quality, the highest proportion of C_{VL} (very labile carbon, 43.5%) was found under cocoa trees, followed by C_{NL} (non-labile carbon) with 28.2%, and in small proportion, labile carbon (C_L, 15.8%) and less labile carbon (C_{LL}, 12.3%).

Financial outcomes: They have not been recorded/provided yet.

Outreach: The research trial has served as a living lab to conduct applied research, including one doctoral thesis, five master theses, and seven undergraduate research projects. A technical

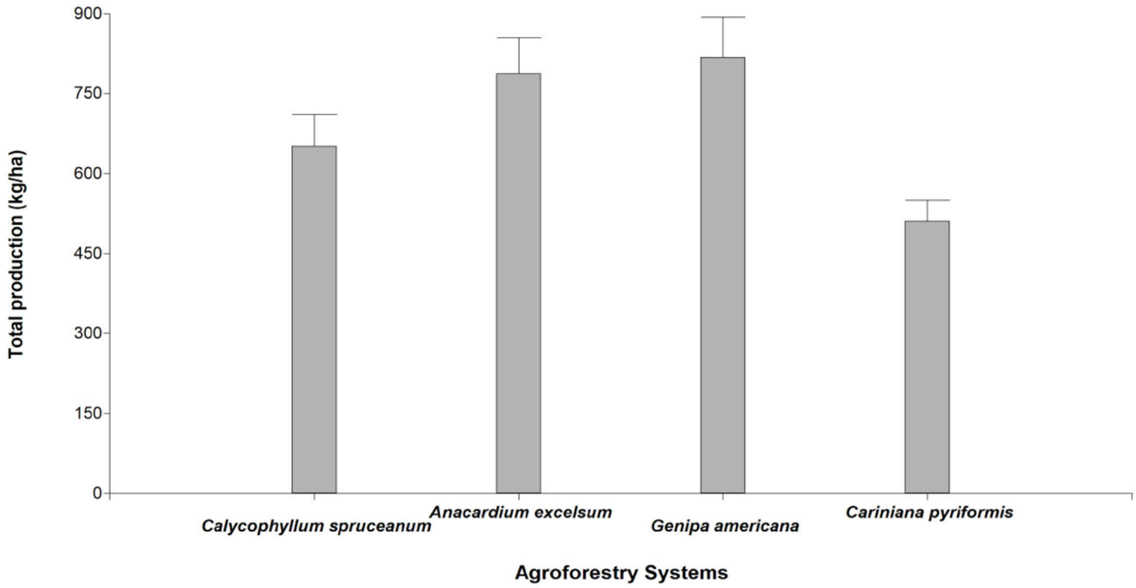

FIGURE 12
Accumulated cacao yields (2018–2022) under four different agroforestry systems in the CIMAZ experimental site, Amazonia, Colombia.

course on shaded cacao cultivation is offered annually, where 200 farmers and students have been trained.

Featured trial #5. Design, production, and environmental value of cacao cultivation models in the Atlantic forest and Amazon biomes in Brazil

Between 2004 and 2010, the CEPLAC Ministry of Agriculture, Livestock, and Food Supply partnered with private actors and organized farmers to implement at least eight different cacao-based agroforestry models across the main production regions in Brazil (MAPA-CEPLAC, 2011) (Figure 13). At the farm level, each cultivation model performed differently in terms of cacao yield, shade canopy products, and, hence, financial revenues to farmers (Table 3). At the landscape level, these cacao cultivation models created an interconnected agroforestry mosaic with natural forests that can be considered climate-smart agriculture, balancing biodiversity protection and commercial production (Schroth et al., 2016a,b). The adoption potential of a given cultivation model is dictated by the productivity and profitability achieved over time. Design features and economic considerations with an emphasis on the yields provided by cacao and the consort of associated shade species are presented elsewhere (Gama-Rodrigues et al., 2021).

The establishment of several cacao-based agroforestry systems by CEPLAC/MAPA considered four key design and management aspects for sustainable agriculture:

a) Technical efficiency: It allows for more efficient control of cacao diseases since crop models implemented use proven practices to increase productivity.
b) Social importance: Given that mechanization is not entirely feasible, cacao farming should use fixed labor while providing long-term sources of income for rural families.
c) Economic sustainability: Projects were usually developed in small modules (≤5 ha) and relied on the family workforce to reduce production costs and withstand price fluctuations.
d) Ecological coherence: Crop models should offer several ecological benefits at the farm and landscape levels, both of which are of great relevance to the primary sector across the Amazon.

Section #3. Learning from the CacaoFIT network

The genetic pool of cacao, cultivation models, and a pallet of agro-environmental information throughout the CacaoFIT network provide fruitful insights to several actors along the value chain. New LAC farmers aiming at simultaneously producing acceptable cacao yields and timber at different time frames might review both FHIA and CATIE trials in humid-lowland Honduras, Costa Rica, and Panama, respectively (Somarriba and Beer, 2011; Ramírez-Argueta et al., 2022). Other meaningful insights from timber-based agroforestry systems are also well documented in Venezuela (Jaimez et al., 2013), Colombia (Agudelo-Castañeda et al., 2018), and Brazil (Gama-Rodrigues et al., 2021), all experimental sites included in this study. Moreover, farmers interested in managing cacao plantations under organic or conventional systems can rely on robust technical and scientific support from the SysCom trial in Alto Beni, Bolivia (SysCom Trial), and several medium-sized trials across Colombia (Agrosavia, Fedecacao, Universidad de la Amazonia), which tested the tree growth of valuable timber species and novel cropping systems, proving suitable for both small and medium-scale farmers.

LAC farmers searching for innovative methods of growing cacao under a diversified shade canopy maybenefit from the insights gained through the CIRAD-led CacaoForest network

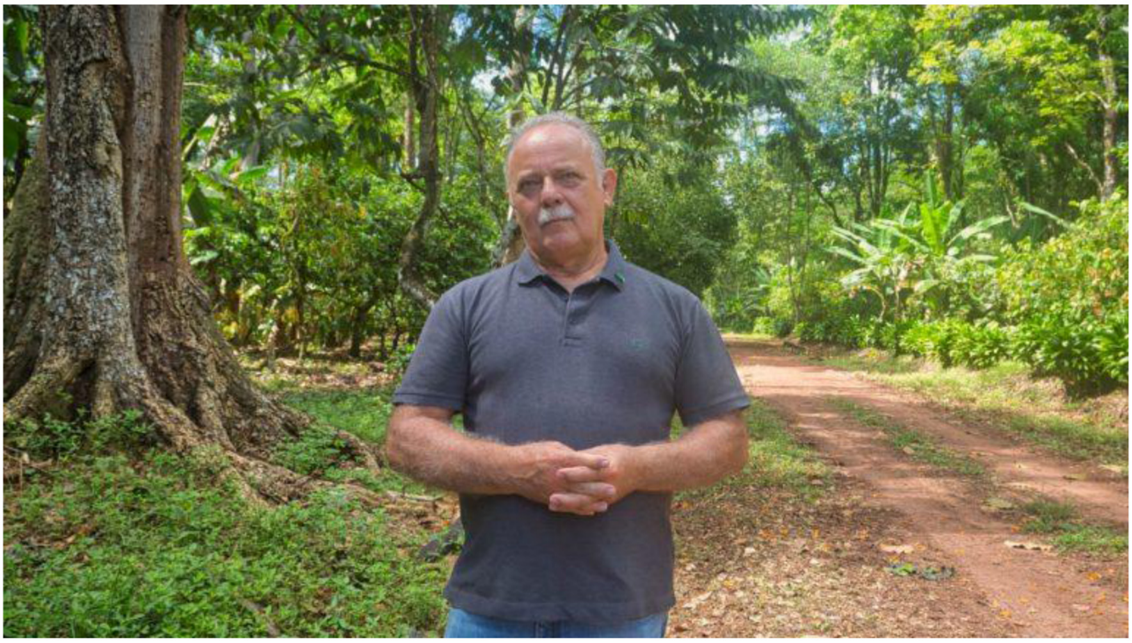

FIGURE 13
Dr. Fernando Texeira Mendes, a researcher at the Executive Commission for Cacao Cultivation Planning (CEPLAC), in the Estação de Recursos Genéticos José Haroldo, in Marituba, Pará, the world's largest cacao genebank, which hosts more than 53,000 cacao plants. Image by Miguel Pinheiro.

TABLE 3 Planted area and main design features of cacao cultivation models tested by CEPLAC-MAPA in the Atlantic and Amazon biomass in Brazil.

Agroforestry models (AFS)	Cultivated area (ha) across the Atlantic and Amazon biomes	Cacao density (plants/ha)	Shade density (trees/ha)	Dominant species	Yields (kg/ha) and timber*
Cacao + Forest Trees	This AFS has been used since 1973 in Rondônia and currently covers ~9,000 ha and 140,000 ha in the state of Para.	1,111	70 and 256 bananas	*Schizolobium amazonicum, Tabebuia heptaphylla, C. alliodora, Bagassa guianensis B. excelsa and S. macrophylla*	1,200/55 m^3 ha^{-1} of timber
Cacao + peach palm + timber	This AFS occupies ~1,245 ha in the states of Mato Grosso and Para.	1,145	575 peach palms + 84 timber trees	*B. gasipaes, C. allidora*	1,170/45 m^3 ha^{-1} of timber
Cacao + coconut palm + yellow mombin	Approximately 100 ha of cacao under this AFS in the State of Amazonas	740	123 coconut and + 25 yellow mombin	*Cocos nucifera + Spondias mombin*	1,250/
Cacao + coffee (*C. canephora*) + teak	This AFS occupies nearly 1,765 ha in the states of Amazonas, Mato Grosso, and Spirito Santo.	945 cacao + 1,062 coffee	117 teak	*T. grandis + Coffea canephora*	825/25 m^3 ha^{-1} of timber
Cacao + Teak	This AFS currently covers ~3,600 ha in the States of Bahia and Para.	885	258 peach palms and 64 forest trees	*B. gasipaes and T. grandis*	925/180 m^3 ha^{-1} of timber
Cacao + coconut + Andiroba	This model currently covers ~600 ha in the States of Spirito Santo and Rondônia.	833	800 coffee, 33 coconut and 78 andirobas	*C. nucifera + C. guianensis*	820
Cacao + Rubber tree	The estimated area under old rubber plantations (>20 years) in Bahia is currently ~11,000 ha	833	830 rubber + 144 madreado trees.	*H. brasilensis + G. sepium*	850–1,200
Cacao + Erythrina trees + banana	Currently covers an area of nearly 80,000 ha and was implemented by CEPLAC in the 1960s.	1,111	1111 bananas and 25 Erythrina trees	*Erythrina* sp. + temporal shade provided by *Zea mays* and *Manihot esculenta*	780–900

Sourced from Gama-Rodrigues et al., 2021.
*Yields recorded up to six years after planting. Source: Gama-Rodrigues et al. (2021).

(Notaro et al., 2020, 2021) and the ongoing regional KoLFACI project co-executed by CATIE and several national research institutions (KoLFACI project). Both research networks have yielded meaningful information on diversification strategies, income generation from cacao and agroforestry, and climate-smart agricultural practices. Moreover, farmers planning to renovate or rehabilitate their aging and low-productive cacao fields in a cost-effective manner can review the experience gained by ICT in Peru, where three different renovation pathways (the Improved Native Agroforestry System, the Improved Traditional Agroforestry System, and the Cover Crop System) successfully improved crop yields and soil fertility under organic and conventional regimes (Figure 14). Finally, farmers and investors interested in novel shaded cacao plots could explore the array of agroforestry systems documented across Brazil (Gama-Rodrigues et al., 2021), Mexico (López-Cruz et al., 2021), and Central America (Deheuvels et al., 2012; Cerda et al., 2014).

Development projects such as www.mocca.org, Alianza Cacao El Salvador, Proyecto REVICACAO, private investors including *12T*ree, Ritter Sport-El Cacao, Cacao Oro, and Andean Cocoa, and sectorial platforms, namely SICACAO, ALCACAO, and Climate Smart Cacao, have benefited from the experience documented within the CacaoFIT network. The ICT and Agrosavia research sites generated key inputs and technical guidelines to support nationwide cacao projects (Cocoa Alliance Peru) and Cacao for Peace. Capacity building, dissemination of training materials, sharing findings in forums and seminars, and producing scientific publications were also pivotal in the CacaoFIT network.

The research agenda and outreach from the CacaoFIT network

CacaoFIT's long-term vision is to generate science-based knowledge and technical guidelines for sustainable cacao cultivation across LAC. However, several research gaps were evident from the CacaoFIT research agenda assessment. Agronomy research questions are being addressed by most research trials (specifically linked to cacao growth and yields and the overall incidence of pest and disease under shaded models), while other key topics are under-examined aspects of cacao cultivation. For instance, the dynamic of pod load vs. cacao plant architecture, the effects of pruning regimes (intensity and frequency) on yields (Orozco-Aguilar et al., 2021; Jaimez et al., 2022; Goudsmit et al., 2023) and the allocation of basal area models (Somarriba and López, 2018a) were found to be seldom researched (Nygren et al., 2013; Heming et al., 2022; Schmidt et al., 2022). Exploring the "crowding effects" of cocoa trees and neighboring trees on the per-plant yield will generate more nuanced advice for best practices in planting density (Wibaux et al., 2017; Cilas and Bastide, 2020; Saj et al., 2023). Below-ground interactions such as fine root dynamics, root volume/biomass and exploration profiles were other topics under-researched within the CacaoFIT network.

Agroforestry-related topics such as the effects of shading factors and tree functional traits (Gagliardi et al., 2020, 2021, 2022, 2023; Isaac et al., 2024) on pathogen dynamics (Leandro-Muñoz et al., 2017; Avelino et al., 2020), rainfall partitioning, and microclimate modificationwere still under-researched topics, especially in comparison to coffee agroforestry trials (Padovan et al., 2015; Abdulai et al., 2020). The SysCom trial in Alto Beni, Bolivia, and the CIMAZ research center in Ecuadorian Amazonia were the only research teams exploring such cacao-shade canopy interactions (Niether et al., 2019, 2020; Armengot et al., 2020, 2023; Hernández-Nuñez et al., 2024). The influence of historical weather and microclimate conditions on yields and the dynamics of pests and diseases is an unexplored yet highly pertinent research issue within the CacaoFIT research agenda. Key environmental services at both farm and landscape levels have been studied by several members of the CacaoFIT network, mostly focused on carbon stock and sequestration potential, litter decomposition, and nutrient cycling. However, soil macrofauna, soil moisture/infiltration, pollinator abundance and diversity, and local/migratory birds were studied to a lesser extent (Toledo-Hernández et al., 2020; Ocampo-Ariza et al., 2024). The restoration potential of shaded cacao plots was not a top-ranked topic in the CacaoFIT research agenda (Schroth et al., 2017; Harvey et al., 2021; Fremout et al., 2022; Bennet et al., 2023).

The study of cacao plant physiology and its interactions with associated trees were minimally explored within the CacaoFIT network. Notable research on this topic has been conducted at the experimental site in Merida, Venezuela, and led by the University de Los Andes (Araque et al., 2012; Ávila-Lovera et al., 2016). Nowadays, the experimental trials located at CIMAZ and Agrosavia, both from Colombia, are levering the topic with experimental and modeling work (Suárez Salazar et al., 2018a; Jaimes-Suárez et al., 2022; Carvalho et al., 2023). The remaining CacaoFIT research trials fall short in this regard, presumably due to the lack of instruments, software, and skilled staff. Topics such as rehabilitation or renovation costs and technical guidelines to do so, although needed in the region (Dalberg, 2015; Somarriba and López, 2018b; Riedel et al., 2019), were seldom evaluated. Although key for decision-making and accessing credits, the financial performance of cacao cultivation models was the least researched or published topic within CacaoFIT. This might be a warning call for all CacaoFIT members to agree on a set of key performance indicators to better communicate results to value chain actors. Finally, farmer outreach was strong and dynamic among a few CacaoFIT members, where several actors were trained, technical publications were delivered, and capacity-building spaces were offered. Large-scale dissemination of research findings from the CacaoFIT trial into farmers' hands and university curricula is a much-needed task of this consortium.

The way forward

This dynamic context of cacao cultivation in LAC poses social, economic, and environmental challenges to those in charge of knowledge generation. The delivery of cost-effective technical guidelines for thousands of cocoa farmers is essential.In this study, we documented the novel knowledge generated and published by CacaoFIT members, yet we understand that to properly address the industry challenges, only a coordinated effort by all stakeholders can ensure cocoa profitability and sustainability (Shapiro and Rosenquist, 2004). Here, we identified five key actions to strengthen

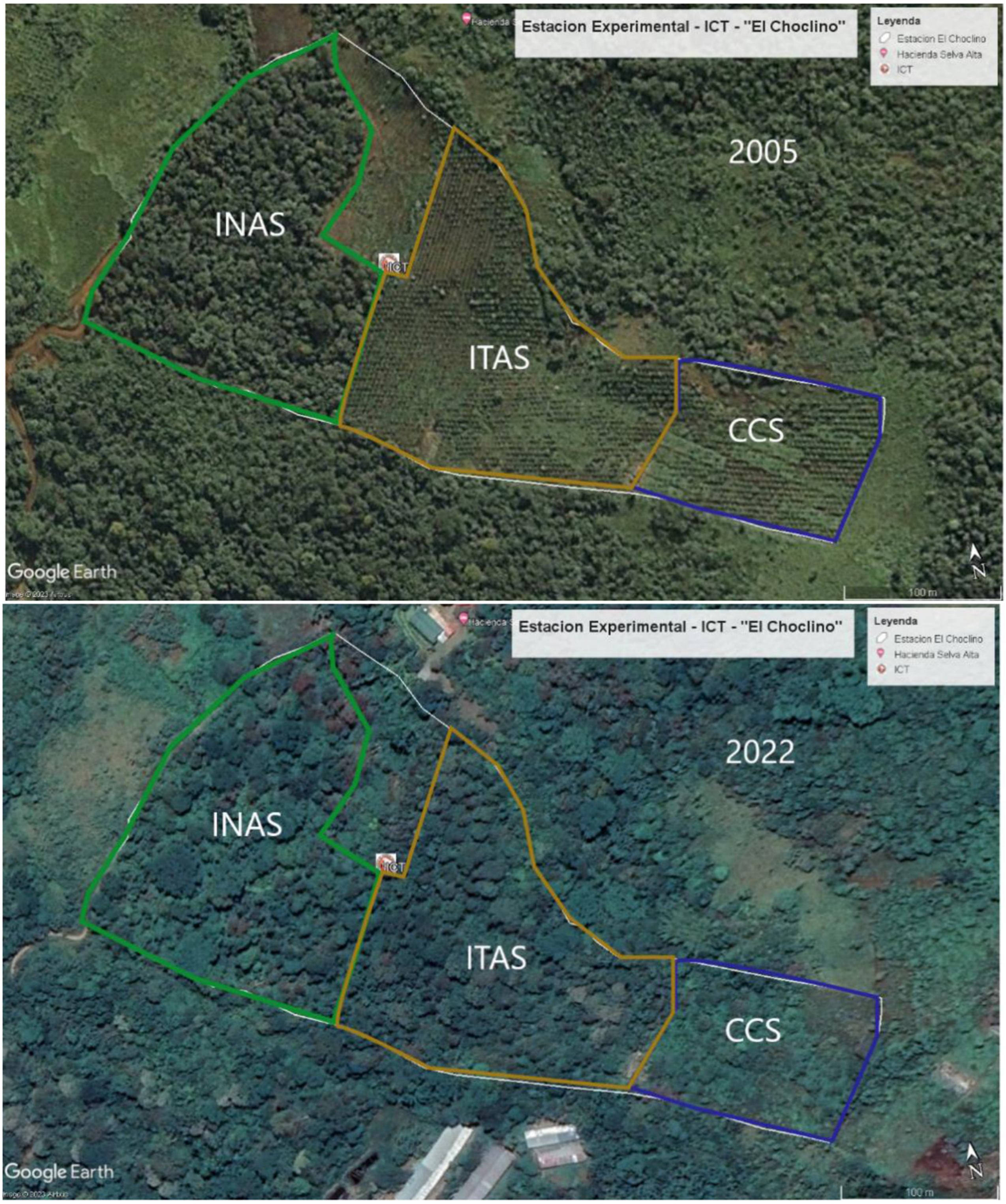

FIGURE 14
Evolution of agroforestry systems established at "El Choclino" research center, ICT, Tarapoto, San Martin, Peru: Improved Native Agroforestry System (INAS), Improved Traditional Agroforestry System (ITAS), and Cover Crops System (CCS) with different cacao genotypes in the Peruvian Amazon. Photo by Arévalo-Hernández et al. (2019).

the research agenda, foster collaboration among the CacaoFIT network, seek alliances between CacaoFIT and third parties, better connect with peers in the global south, and deliver mainstream communication and outreach.

1. **Link and strengthen the research agenda with global research platforms:** CacaoFIT trials and affiliates could be better connected to at least five global research platforms linking cacao farming with sustainability standards: Globalagroforestrynetwork, Agroforesta, Cacaonet, and the Smithsonian Institute. Stronger interaction between CacaoFIT members and international cocoa platforms such as the European Cocoa Association and Nitidae in Africa, INCOCOA, would also be mutually beneficial. Partnering with these platforms might facilitate research protocol sharing, splitting equipment costs, and incorporating software to strengthen research gaps on physiology and the financial performance of shaded cacao.
2. **Collaboration among CacaoFIT members to co-design research projects:** Members of the CacaoFIT network, especially those from South America (e.g., Agrosavia, U. Amazonia, and Fedecacao in Colombia, FiBL-Ecotop in Bolivia, Universidad de Manabi and INIAP in Ecuador, and ICT in Peru), have well-known experimental sites and skilled staff who may collaborate on future research proposals to better respond to national or specific contexts and challenges faced by the cacao sector. Some relevant research funds available are the Fontagro platform, the BID-Lab (https://bidlab.org/es), the Foundation for Food and Agriculture Research (https://foundationfar.org/), the World Cocoa Foundation, ICCO (https://www.icco.org/), and other government-led funds in each country.
3. **Public-private partnerships (PPP):** the existence of major chocolate industry players and private investors in several cacao production countries in LAC is a great opportunity for partnerships and interconnected research missions. Some key actors are Hershey's and Ecom Trading in Mexico (https://www.ecomtrading.com/mexico/), MARS-La Chola in Ecuador (https://www.mars.com/, 12Tree in Guatemala, Panama, Colombia, and the Dominican Republic (https://www.12tree.de/portfolio), Ritter Sport (https://www.ritter-sport.com/el-cacao), and CacaoORO in Nicaragua (https://cacaooro.com/) and Fundo Tamshi in Peru (https://www.tamshicacao.com/home-english), among others. Some topics overlooked in the research agenda of CacaoFIT could be addressed via PPP. These include (a) the survival pod curve for improving yield forecasting methods, (b) links between the length of productive tissue and pruning on tree pod load, (c) breeding new varieties/clones for low cadmium accumulation, (d) screening for new cultivars that are drought and flood-tolerant, and (e) documenting cost-effective strategies for renovation/rehabilitation interventions.
4. **Technical advocacy and training with global South actors**: West and Central Africa (WCA) is currently responsible for 70% of world cocoa production, with an annual output of 3.5 million tons (Hütz-Adams et al., 2022). Over 6 million ha of cocoa are cultivated mainly in open-sun plots or under simple shade canopies (Asare and Anders, 2016; Somarriba et al., 2023). Agroforestry is now widely promoted in cocoa cultivation in WCA to achieve environmental benefits and rural family livelihoods (Asare et al., 2014; Somarriba et al., 2023; Tscharntke et al., 2022; Sonwa et al., 2020). Therefore, the experience accumulated in LAC, and particularly the plethora of cocoa agroforestry systems within the CacaoFIT network, can be used for capacity building and to support the formulation and implementation of sound policies and cacao-agroforestry development projects. Integrating the novel knowledge, technical guidelines, and set of practices devised by CacaoFIT is crucial to achieving the outcomes committed to by global initiatives such as the Cocoa and Forests Initiative.
5. **Pan-institutional communication and outreach for** the production of scientific knowledge from the CacaoFIT network spread over a broad range of topics via scientific papers, technical manuals, fact sheets, and videos. Research outputs need to be organized and disseminated in ways that are most meaningful in supporting sectoral decision-making in both LAC and WCA. Several national and regional cocoa boards, such as Sicacao, Alcacao, APPCacao, Anecacao, and Fedecacao, require data and guidance to better inform the strategic planning of the cocoa industry, certification bodies, and policymakers. Research outcomes from the CacaoFIT network should also be incorporated into the curricula at the university and technical levels to engage youth and women. This will ensure the vitality of the industry with new generations of cacao growers.

Conclusion

CacaoFIT is an active network of medium- to long-term trials acrossLAC that tested several cultivation systems, generated knowledge, validated best practices, and delivered recommendations for farmers, cacao boards, development projects, investors, academia, and decision-makers. Gaps exist in the research agenda of CacaoFIT, mainly concerning cocoa physiology, environmental services, and the financial performance of shaded agroforestry systems. Thus, partnering with academic institutions and private actors in the global south might level up these research topics. CacaoFIT members must better connect to share data, methodologies, and protocols, standardize the data collection process, and formulate joint projects to enhance research outcomes from the network. Greater dissemination of CacaoFIT's research outcomes into academia, formal training, and advocacy by development agencies are required, which, in turn, will motivate public-private cooperation and funding. Finally, the CacaoFIT network has generated ample data and technical guidelines to support agroforestry projects and capacity building in the global south.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding authors.

Ethics statement

The individual(s) provided their written informed consent for the publication of any identifiable images or data presented in this article.

Author contributions

LO-A: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing, Funding acquisition, Validation. AL-S: Conceptualization, Data curation, Formal analysis, Visualization, Writing – original draft, Writing – review & editing, Investigation, Supervision. RC: Writing – original draft, Writing – review & editing. FC: Data curation, Formal analysis, Validation, Writing – original draft, Writing – review & editing. OR-A: Writing – review & editing, Writing – original draft. JD: Writing – review & editing, Writing – original draft. JS: Writing – original draft, Writing – review & editing. JR: Writing – original draft, Writing – review & editing. SS: Writing – original draft, Writing – review & editing. JM: Writing – original draft, Writing – review & editing. US: Writing – original draft, Writing – review & editing. AM: Writing – original draft, Writing – review & editing. JRM: Writing – original draft, Writing – review & editing. YJ: Writing – original draft, Writing – review & editing. EBD: Writing – review & editing, Writing – original draft. GA: Writing – original draft, Writing – review & editing. OD: Writing – original draft, Writing – review & editing. EBS: Writing – original draft, Writing – review & editing. JG: Writing – original draft, Writing – review & editing. RJ: Writing – original draft, Writing – review & editing. MB: Writing – original draft, Writing – review & editing. SR: Writing – original draft, Writing – review & editing. JP: Writing – original draft, Writing – review & editing. AA: Writing – original draft, Writing – review & editing. LS: Writing – original draft, Writing – review & editing. MS-M: Writing – original draft, Writing – review & editing. CA-H: Writing – original draft, Writing – review & editing. EA: Writing – original draft, Writing – review & editing. LP: Writing – original draft, Writing – review & editing. AG-R: Writing – original draft, Writing – review & editing. EG-R: Writing – original draft, Writing – review & editing. AK: Writing – original draft, Writing – review & editing. ESM: Writing – original draft, Writing – review & editing. PU: Writing – original draft, Writing – review & editing. GR: Writing – original draft, Writing – review & editing. AH: Writing – original draft, Writing – review & editing. PA: Writing – original draft, Writing – review & editing. OD: Writing – original draft, Writing – review & editing. OA: Writing – original draft, Writing – review & editing. GP: Writing – original draft, Writing – review & editing. LT: Writing – original draft, Writing – review & editing. CC: Writing – original draft, Writing – review & editing. MW: Writing – original draft, Writing – review & editing. FT: Writing – original draft, Writing – review & editing. ES: Writing – original draft, Writing – review & editing.

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Conflict of interest

LO-A was employed by CATIE as Regional Tropical Agroforestry Consultant. AM, EB, JR, YJ, GA were employed by Agrosavia.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1370275/full#supplementary-material

References

Abdulai, I., Hoffmann, M. P., Jassogne, L., Asare, R., Graefe, S., Tao, H.-H., et al. (2020). Variations in yield gaps of smallholder cocoa systems and the main determining factors along a climate gradient in Ghana. *Agric. Syst.* 181:102812. doi: 10.1016/j.agsy.2020.102812

Agudelo-Castañeda, G. A., Antolinez-Sandoval, E. Y., Báez-Daza, E. Y., Jaimes-Suárez, Y. Y., and Romero-Guerrero, G. A. (2023). New cocoa varieties selected in Colombia. *Revista Mexicana de Ciencias Agrícolas* 14, 315–326. doi: 10.29312/remexca.v14i3.3057

Agudelo-Castañeda, G. A., Cadena-Torres, J., Almanza-Merchán, P. J., and Pinzón-Sandoval, E. H. (2018). Physiological performance of nine cacao (*Theobroma cacao* L.) genotypes under the shadow of three forest species in Santander, Colombia. *Revista Colombiana de Ciencias Hortícolas* 12, 223–232. doi: 10.17584/rcch.2018v12i1.7341

Araque, O., Jaimez, E. R., Teraza, W., Coronel, I., Uricj, R., and Espinoza, W. (2012). Photosynthesis, water relations, growth and survival rates in juveniles criollo cacao cultivar during dry and we seasons. *Exp. Agricult.* 48, 513–522. doi: 10.1017/S0014479712000427

Arévalo-Hernández, C. O., da Conceição Pinto, F., de Souza Júnior, J. O., de Queiroz Paiva, A., and Baligar, V. C. (2019). Variability and correlation of physical attributes of soils cultivated with cacao trees in two climate zones in Southern Bahia, Brazil. *Agrofor. Syst.* 93, 793–802. doi: 10.1007/s10457-017-0176-4

Armengot, L., Barbieri, P., Andres, C., Milz, J., and Schneider, M. (2016). Cacao agroforestry systems have a higher return on labor compared to full-sun monocultures. *Agron. Sustain. Dev.* 36:70. doi: 10.1007/s13593-016-0406-6

Armengot, L., Beltrán, M. J., Schneider, M., Simón, X., and Pérez-Neira, D. (2021). Food-energy-water nexus of different cacao production systems from a LCA approach. *J. Clean. Prod.* 304, 126941. doi: 10.1016/j.jclepro.2021.126941

Armengot, L., Ferrari, L., Milz, J., Velásquez, F., Hohmann, P., and Schneider, M. (2020). Cacao agroforestry systems do not increase pest and disease incidence compared with monocultures under good cultural management practices. *Crop Prot.* 130, 105047. doi: 10.1016/j.cropro.2019.105047

Armengot, L., Picucci, M., Milz, J., Hansen, J. K., and Schneider, M. (2023). Locally-selected cacaoclones for improved yield: a case study indifferent production systems in a long-termtrial. *Front. Sustain. Food Syst.* 7:1253063.doi: 10.3389/fsufs.2023.1253063

Asare, R., Afari-Sefa, V., Osei-Owusu, Y., and Pabi, O. (2014). Cocoa Agroforestry for increasing forest connectivity in a fragmented landscape in Ghana. *Agrofor Syst.* 88, 1143–1156 doi: 10.1007/s10457-014-9688-3

Asare, R., and Anders, R. (2016). Tree diversity and canopy cover in cocoa systems in Ghana. *New Forests* 47, 287–230. doi: 10.1007/s11056-015-9515-3

Avelino, J., Vílchez, S., Segura-Escobar, M. B., Brenes-Loaiza, M. A., Virginio Filho, E. M., and Casanoves, F. (2020). Shade tree Chloroleucon eurycyclum promotes coffee leaf rust by reducing uredospore wash-off by rain. *Crop Prot.* 129:105038. doi: 10.1016/j.cropro.2019.105038

Ávila-Lovera, E., Coronel, I., Jaimez, R., Urich, R., Pereyra, P., Araque, O., et al. (2016). Ecophysiological traits of adult trees of Criollo cacao cultivars (*Theobroma cacao* L.) from a germplasm bank. *Exp. Agric.* 52, 137–153. doi: 10.1017/S0014479714000593

Beer, J., Muschler, R., and Kass, D. (1998). Shade management in coffee and cacao plantations. *Agroforest. Syst.* 38, 139–164. doi: 10.1023/A:1005956528316

Bennet, R. E., Sillett, T. S., Rice, R. A., and Marra, P. P. (2023). Impact of cocoa agricultural intensification on bird diversity and community composition. *Conserv. Biol.* 36:e13779. doi: 10.1111/cobi.13779

Carvalho, F. E., Escobar-Pachajoa, L. D., Camargo, I. D., Rojas-Molina, J., Jaimes-Suárez, Y. Y., and Rivera-Meneses, J. J. (2023). The interspecific interactions in agroforestry systems enhance leaf water use efficiency and carbon storage in cocoa. *Environ. Exp. Bot.* 205, 105119. doi: 10.1016/j.envexpbot.2022.105119

Ceccarelli, V., Fremout, T., Zavaleta, D., Lastra, S., Imán Correa, S., Arévalo-Gardini, E., et al. (2021). Climate change impact on cultivated and wild cacao in Peru and the search of climate change tolerant-genotypes. *Divers. Distribut.* 27, 1462–1476 doi: 10.1111/ddi.13294

Cerda, R., Deheuvels, O., Calvache, D., Niehaus, L., Saenz, Y., Kent, J., et al. (2014). Contribution of cocoa agroforestry systems to family income and domestic consumption: looking toward intensification. *Agrofor. Syst.* 88, 957–981. doi: 10.1007/s10457-014-9691-8

Chavez, E., He, Z. L., Stoffella, P. J., Mylavarapu, R. S., Li, Y. C., Moyano, B., et al. (2015). Concentration of cadmium in cacao beans and its relationship with soil cadmium in southern Ecuador. *Sci. Total Environ.* 15, 205–214. doi: 10.1016/j.scitotenv.2015.06.106

Cilas, C., and Bastide, P. (2020). Challenges to cocoa production in the face of climate change and the spread of pests and diseases. *Agronomy* 10:1232. doi: 10.3390/agronomy10091232

Dalberg (2015). *Smallholder tree crop renovation and rehabilitation(R&R). A review of the State of the emerging R&R market and opportunities to scale investment*. Utrecht: IDH The Sustainable Trade Initiative, 78

Daymond, A., Giraldo, D., Hadley, P., and Bastide, P. (eds.). (2022). *A Global Guide to Cocoa Farming Systems.* Reading: University of Reading, 35.

Deheuvels, O., Avelino, J., Somarriba, E., and Malezieux, E. (2012). Vegetation structure and productivity in cocoa-based agroforestry systems in Talamanca, Costa Rica. *Agric. Ecosyst. Environ.* 149, 181–188. doi: 10.1016/j.agee.2011.03.003

FEDECACAO (2020). *Caracterización de productores de cacao en Colombia*. Resultados del Diagnóstico Nacional. Available online at: https://app.powerbi.com/view?r=eyJrIjoiMWYyNzE2YzMtY2FlOS00OGJjLTkyZmQtNzY3MjM5M2QyZWI1IiwidCI6IjFlMTY3MDEwLTgwM2QtNDA4My1hYzZhLTVlNmE0Zjc1YzM2YyIsImMiOjR9 (Retrieved March 15, 2021).

FiBL (2023). Available online at: https://systems-comparison.fibl.org/project-sites/bolivia.html

Fountain, A. C. (2022). *Cocoa Barometer Living Income Compendium.* The Cocoa Barometer Consortium. Available online at: https://voicenetwork.cc/wp-content/uploads/2022/09/220920-Cocoa-Barometer-Living-Income-Compendium.pdf

Fremout, T., Thomas, E., Taedoumg, H., Briers, S., Gutiérrez-Miranda, C. E., Alcázar-Caicedo, C., et al. (2022). Diversity for restoration (D4R): guiding the selection of tree species and seed sources for climate-resilient restoration of tropical forest landscapes. *J. Appl. Ecol.* 59, 664–679. doi: 10.1111/1365-2664.14079

Gagliardi, S., Avelino, J., Beilhe, L. B., and Isaac, M. E. (2020). Contribution of shade trees to wind dynamics and pathogen dispersal on the edge of coffee agroforestry systems: a functional traits approach. *Crop Prot.* 130:105071. doi: 10.1016/j.cropro.2019.105071

Gagliardi, S., Avelino, J., Fulthorpe, R., Virginio Filho, E. M., and Isaac, M. E. (2022). No evidence of foliar disease impact on crop root functional strategies and soil microbial communities: what does this mean for organic coffee? *Oikos* 2023:e08987. doi: 10.1111/oik.08987

Gagliardi, S., Avelino, J., Martin, A. R., Cadotte, M., Virginio Filho, E. M., and Isaac, M. E. (2023). Leaf functional traits and pathogens: linking coffee leaf rust with intraspecific trait variation in diversified agroecosystems. *Plos ONE* 18:e0284203. doi: 10.1371/journal.pone.0284203

Gagliardi, S., Avelino, J., Virginio Filho, E. M., and Isaac, M. E. (2021). Shade tree traits and microclimate modifications: implications for pathogen management in biodiverse coffee agroforests. *Biotropica* 53, 1356-1367. doi: 10.1111/btp.12984

Gama-Rodrigues, A. C., Müller, M. W., Gama-Rodrigues, E. F., and Teixeira Mendes, F. A. (2021). Cacao-based agroforestry systems in the Atlantic Forest and Amazon Biomes: an ecoregional analysis of land use. *Agric. Syst.* 194:103270. doi: 10.1016/j.agsy.2021.103270

Garcia-Briones, A., Pico-Pico, P., and Jaimez, E. (2021). The Cacao production chain in Ecuador: Resilience in the different production actors. *Novasinergia* 4, 152–172. doi: 10.37135/ns.01.08.10

Goudsmit, E., Rozendaal, D. A. A., Tosto, A., and Slingerland, M. (2023). Effects of fertilizer application on cacao pod development, pod nutrient content and yield. *Scientia Horticulturae* 313:111869. doi: 10.1016/j.scienta.2023.111869

Hartemink, A. E. (2005). Nutrient stocks, nutrient cycling, and soilchanges in cacao ecosystems: a review. *Adv Agron.* 86, 227–253 doi: 10.1016/S0065-2113(05)86005-5

Harvey, C. A., Pritts, A. A., Zwetsloot, M. J., Jansen, K., Pulleman, M. M., Armbrecht, I., et al. (2021). Transformation of coffee-growing landscapes across Latin America. A review. *Agron. Sustain. Dev.* 41:62. doi: 10.1007/s13593-021-00712-0

Heming, N. M., Schroth, G., Talora, D. C., and Faria, D. (2022). Cabruca agroforestry systems reduce vulnerability of cacao plantations to climate change in southern Bahia. *Agron. Sustain. Dev.* 42:48. doi: 10.1007/s13593-022-00780-w

Hernández-Nuñez, H. E., Suárez, J. C., Andrade, H. J., Acosta, J. R. S., Núñez, R. D., Gutiérrez, D. R., et al. (2024). Interactions between climate, shade canopy characteristics and cocoa production in Colombia. *Front. Sustain. Food Syst.* 8:1295992. doi: 10.3389/fsufs.2024.1295992

Hütz-Adams, F., Campos, P., and Fountain, A. C. (2022). *Latin America Baseline Cocoa Barometer, 2022*. The Cocoa Barometer Consortium, 37. Available online at: https://voicenetwork.cc/wp-content/

Isaac, M. E., Gagliardi, S., Ordoñez, J. C., and Sauvadet, M. (2024). Shade tree trait diversity and functions in agroforestry systems: a review of which traits matter. *J. Appl. Ecol.* 61, 1159–1173. doi: 10.1111/1365-2664.14652

Jacobi, J., Andres, C., Schneider, M., Pillco, M., Calizaya, P., Rist, S., et al. (2014). Carbon stocks, tree diversity, and the role of organic certification in different cocoa production systems in Alto Beni, Bolivia. *Agrofor. Syst.* 88, 1117–1132. doi: 10.1007/s10457-013-9643-8

Jaimes-Suárez, Y. Y., Carvajal-Rivera, A. S., Galvis-Neira, D. A., Carvalho, F. E. L., and Rojas-Molina, J. (2022). Cacao agroforestry systems beyond the stigmas: biotic and abiotic stress incidence impact. *Front. Plant Sci.* 13:921469. doi: 10.3389/fpls.2022.921469

Jaimez, R., Loor, R., Arteaga, F., Márquez, V., and Tezara, W. (2022). Differential response of photosynthetic activity, leaf nutrient content and yield to long-term drought in cacao clones. *Acta Agron.* 70. doi: 10.15446/acag.v70n3.92252

Jaimez, R. E., Araque, O., Guzmán, D., Mora, A., Espinoza, W., Tezara, W., et al. (2013). Agroforestry systems of timber species and cacao: survival and growth during the early stages. *J. Agr. Rural Develop. Trop. Subtrop.* 114, 1−11. Available online at: https://jarts.info/index.php/jarts/article/view/2012112642171

Kottek, M., Grieser, J., Beck, C. H., Dudolg, B., and Ranz, R. (2006). World map of the Köppen-Geiger climate classification updated. *Meteorologische Zeitschrift.* 15, 259–263. doi: 10.1127/0941-2948/2006/0130

Leandro-Muñoz, M. E., Tixier, P., Germon, A., Rakotobe, V., and Phillips-Mora,W., Maximova, S., et al. (2017). Effects of microclimatic vari-ables on the symptoms and signs onset of Moniliophthora roreri,causal agent of Moniliophthora pod rot in cacao. *PLoS ONE*. 12:e0184638. doi: 10.1371/journal.pone.0184638

López-Cruz, A., Soto-Pinto, L., Salgado-Mora, M. G., and Huerta-Palacios, G. (2021). Simplification of the structure and diversity of cocoa agroforests does not increase yield nor influence frosty pod rot in El Soconusco, Chiapas, Mexico. *Agrofor. Syst.* 95, 201–214. doi: 10.1007/s10457-020-00574-7

Loukos, P. (2020). *Landscaping the agritech ecosystem for smallholder farmers in Latin America and the Caribbean/Panos Loukos, Leslie Arathoon; coordinators, Alejandro Escobar, Sergio Navajas— Inter-American Development Bank (IDB Technical Note; 2084).* Inter-American Development Bank (IDB) LAB. Available online at: www.bidlab.org; https://publications.iadb.org/en/landscaping-agritech-ecosystem-smallholder-farmers-latin-america-and-caribbean

Magne, A. N., Nonga, N. E., Yemefack, M., et al. (2014). Profitability and implications of cocoa intensification on carbon emissions in Southern Cameroun. *Agroforest Syst* 88, 1133–1142 doi: 10.1007/s10457-014-9715-4

MAPA-CEPLAC (2011). *Ministry of Agriculture, Livestock and Food Supply/Executive Commission of the Cacao Farming Plan*. MAPA/ACS. Technical Report, 61.

Marconi, L., and Armengot, L. (2020). Complex agroforestry systems against biotic homogenization: the case of plants in the herbaceous stratum of cocoa production systems. *Agric. Ecosyst. Environ.* 287:106664. doi: 10.1016/j.agee.2019.106664

Mazón, M., Sánchez-Angarita, D., Díaz, F. A., Gutiérrez, N., and Jaimez, R. (2018). Entomofauna associated with agroforestry systems of timber species and cacao in the southern region of the maracaibo lake basin (Mérida, Venezuela). *Insects* 9:46. doi: 10.3390/insects9020046

Middendorp, R. S., Vanacker, V., and Lambin, E. F. (2018). Impacts of shaded agroforestry management on carbon sequestration, biodiversity and farmers income in cocoa production landscapes. *Landscape Ecol.* 33, 1953–1974. doi: 10.1007/s10980-018-0714-0

Montealegre Bustos, F., Rojas Molina, J., and Jaimes Suárez, Y. (2021). Factores agronómicos y socioecon?micos que inciden en el rendimiento productivo del cultivo de cacao. *Un estudio de cacao en Colombia. Rev. FAVE Cienc. Agrarias* 20, 59–73.

Niether, W., Armengot, L., Andres, C., Schneider, M., and Gerold, G. (2018). Shade trees and tree pruning alter throughfall and microclimate in cocoa (*Theobroma cacao* L.) production systems. *Ann. For. Sci.* 75:38. doi: 10.1007/s13595-018-0723-9

Niether, W., Jacobi, J., Blaser, W. J., Andres, C., and Armengot, L. (2020). Cocoa agroforestry systems versus monocultures: a multi-dimensional meta-analysis. *Environ. Res. Lett*. 15 :104085. doi: 10.1088/1748-9326/abb053

Niether, W., Schneidewind, U., Armengot, L., Adamtey, N., Schneider, M., and Gerold, G. (2017). Spatial-temporal soil moisture dynamics under different cocoa production systems. *CATENA* 158, 340–349. doi: 10.1016/j.catena.2017.07.011

Niether, W., Schneidewind, U., Fuchs, M., Schneider, M., and Armengot, L. (2019). Below-and aboveground production in cocoa monocultures and agroforestry systems. *Sci. Total Environ.* 657, 558-567. doi: 10.1016/j.scitotenv.2018.12.050

Notaro, M., Collado, C., Depas, J. K., Dumovil, D., Aquino, J. D., Deheuvels, O., et al. (2021). The spatial distribution and height of associated crops influence cocoa tree productivity in complex agroforestry systems. *Agron. Sustain. Develop.* 41, 60. doi: 10.1007/s13593-021-00716-w

Notaro, M., Gary, C., and Deheuvels, O. (2020). Plant diversity and density in cocoa-based agroforestry systems: how farmers' income is affected in the Dominican Republic. *Agrofor. Syst.* 94, 1071–1084. doi: 10.1007/s10457-019-00472-7

Nygren, P., Leblanc, H. A., Lu, M., and Luciano, C. (2013). Distribution of coarse and fine roots of *Theobroma cacao* and shade tree *Inga edulis* in a cocoa plantation. *Ann. For. Sci.* 70, 229–239 doi: 10.1007/s13595-012-0250-z

Ocampo-Ariza, C., Hanf-Dressler, T., Maas, B., Novoa-Cova, J., Thomas, E., Vansynghel, J., et al. (2024). Regional differences of functional and taxonomic bird diversity in tropical agroforests of Peru. *Conserv. Sci. Pract*. 6:e13123. doi: 10.1111/csp2.13123

Orozco-Aguilar, L., López-Sampson, A., Leandro-Muñoz, M. E., Robiglio, V., Reyes, M., Bordeaux, M., et al. (2021). Elucidating pathways and discourses linking cocoa cultivation to deforestation, reforestation, and tree cover change in Nicaragua and Peru. *Front. Sustain. Food Syst*. 5:635779. doi: 10.3389/fsufs.2021.635779

Padovan M. P., Cortez, V. J., Navarrete, L. F., Navarrete, E. D., Deffner, A. C., Centeno, L. G., et al. (2015). Root distribution and water use in coffee shaded with *Tabebuia rosea* Bertol and *Simarouba glauca* DC. compared to full-sun coffee in sub-optimal environmental conditions. *Agroforest. Syst.* 89, 857–868. doi: 10.1007/s10457-015-9820-z

Pérez-Neira, D., Copena, D., Armengot, L., and Simón, X. (2020). Transportation can cancel out the ecological advantages of producing organic cacao: the carbon footprint of the globalized agrifood system of Ecuadorian chocolate. *J. Environ. Manage.* 276:111306. doi: 10.1016/j.jenvman.2020.111306

Pérez-Neira, D., Schneider, M., Esche, L., and Armengot, L. (2023). Sustainability of food security in different cacao production systems: a land, labour, energy and food quality nexus approach. *Resour. Conserv. Recycl.* 190:106874. doi: 10.1016/j.resconrec.2023.106874

Ramirez, O., Somarriba, E., Ludewigs, T., and Ferreira, P. (2001). Financial returns, stability and risk of cacao-plantain-tim-ber agroforestry systems in Central America. *Agrofor. Syst.* 51, 141–154. doi: 10.1023/A:1010655304724

Ramírez-Argueta, O., Orozco-Aguilar, L., Dubón, A. D., Díaz, F. J., Sánchez, J., and Casanoves, F. (2022). Timber growth, cacao yields, and financial revenues in a long-term experiment of cacao agroforestry systems in northern Honduras. *Front. Sustain. Food Syst*. 6:941743. doi: 10.3389/fsufs.2022.941743

Riedel, J., Kägi, N., Armengot, L., and Schneider, M. (2019). Effects of rehabilitation pruning and agroforestry on cacao tree development and yield in an older full-sun plantation. *Exp. Agric.* 55, 849–865. doi: 10.1017/S0014479718000431

Rojas-Molina, J., Caicedo, V., and Jaimes, Y. (2017). Biomass decomposition dynamic in agroforestry systems with *Theobroma cacao* L. in Rionegro, Santander (Colombia). *Agron. Colomb.* 35, 182–189. doi: 10.15446/agron.colomb.v35n2.60981

Rüegg, J., Yana, W., Yana, A., Choque, B., Campos, C., and Milz, J. (2024). *Dynamic cocoa agroforestry: 25 years of experience in Alto Beni, Bolivia. Tropical Forest Issues #62.* Ede: Tropenbos International. doi: 10.55515/ZSYD1745

Saj, S., Jagoret, P., Ngnogue, H. T., and Tixier, P. (2023). Effect of neighbouring perennials on cocoa tree pod production in complex agroforestry systems in Cameroon. *Eur. J. Agron.* 146:126810. doi: 10.1016/j.eja.2023.126810

Saj, S., Jagoret, P., and Todem Ngogue, H. (2013). Carbon storage anddensity dynamics of associated trees in three contrasting *Theobrama cacao* agroforests of Central Cameroon. *Agrofor. Syst* 87, 1309–1320. doi: 10.1007/s10457-013-9639-4

Sauvadet, M., Asare, R., and Isaac, M. E. (2020). Evolutionary distance explains shade tree selection in agroforestry systems. *Agric. Ecosyst. Environ*. 304:107125. doi: 10.1016/j.agee.2020.107125

Sauvadet, M., Dickinson, A. K., Somarriba, E., Mora, W. P., Cerda, R., Martin, A., et al. (2021). Genotype–environment interactions shape leaf functional traits of cacao in agroforests. *Agron. Sustain. Dev.* 41, 31 doi: 10.1007/s13593-021-00690-3

Schmidt, J. E., Duval, A., Isaac, M. E., and Hohmann, P. (2022). At the roots of chocolate: understanding and optimizing the cacao root-associated microbiome for ecosystem services. *A review. Agron. Sustain. Dev*. 42:14. doi: 10.1007/s13593-021-00748-2

Schneider, M., Andres, C., Trujillo, G., Alcon, F., Amurrio, P., Perez, E., et al. (2017). Cocoa and total system yields of organic and conventional agroforestry vs. monoculture 470 systems in a long-term field trial in Bolivia. *Exper. Agric.* 53, 351–374. doi: 10.1017/S0014479716000417

Schroth, G., Garcia, E., Griscom, B. W., Teixeira, W. G., and Barros, L. P. (2016a). Commodity production as restoration driver in the Brazilian Amazon? Pasture re-agro-forestation with cocoa (Theobroma cacao) in southern Pará. *Sustain. Sci.* 11, 277–293. doi: 10.1007/s11625-015-0330-8

Schroth, G., Läderach, P., Martinez-Valle, A. I., and Bunn, C. (2017). From site-level to regional adaptation planning for tropical commodities: cocoa in West Africa. *Mitig. Adapt. Strateg. Glob. Change* 22, 903–927. doi: 10.1007/s11027-016-9707-y

Schroth, G., Läderach, P., Martinez-Valle, A. I., Bunn, C., and Jassogne, L. (2016b). Vulnerability to climate change of cocoa in West Africa: patterns, opportunities and limits to adaptation. *Sci. Total Environ.* 556, 231–241. doi: 10.1016/J.SCITOTENV.2016.03.024

Shapiro, H. Y., and Rosenquist, E. (2004). Public/private partnerships in agroforestry: the example of working together to improve cocoa sustainability. *Agrofor. Syst.* 61, 453–462. doi: 10.1007/978-94-017-2424-1_31

Solidaridad (2023). *Cocoa Living Income Latin America Inventory*. Technical Report, 31. Available online at: https://www.solidaridadnetwork.org/wp-content/uploads/2023/07/LIVING-INCOME-INVENTORY_COCOA-LATAM_FINAL_24042023.pdf

Somarriba, E., and Beer, J. (2011). Productivity of Theobroma cacao agroforestry systems with timber or legume service shade trees. *Agrofor. Syst.* 8, 109–121. doi: 10.1007/s10457-010-9364-1

Somarriba, E., and Lachenaud, P. (2013). Successional cocoa agroforests of the Amazon-Orinoco-Guiana shield. *For. Trees Livelihoods* 22, 51–59. doi: 10.1080/14728028.2013.770316

Somarriba, E., and López, A. (2018a). "Coffee and cocoa agroforestry systems: pathways to deforestation, reforestation, and tree cover change," in *Innovation and Action for Forests* (Turrialba, Costa Rica: CATIE), 30.

Somarriba, E., and López, S. A. (2018b). *Coffee and Cocoa Agroforestry Systems: Pathways to Deforestation, Reforestation, and Tree Cover Change*. Washington, DC: LEAVES-The World Bank.

Somarriba, E., Orozco-Aguilar, L., Cerda, R., and López-Sampson, A. (2018). "Analysis and design of the shade canopy of cocoa-based agroforestry system," in *Achieving Sustainable Cultivation of Cocoa*, ed. P. Umaharan (Cambridge: Burleigh Dodds Science Publishing), 469–499. doi: 10.19103/AS.2017.0021.29

Somarriba, E., Saj, S., Orozco-Aguilar, L., Somarriba, A., and Rapidel, B. (2023). Shade canopy density variables in cocoa and coffee agroforestry systems. *Agrofor. Syst*. 98, 585–601. doi: 10.1007/s10457-022-00784-1

Sonwa, D. J., Oumarou Farikou, M., Martial, G., and Félix, F. L. (2020). Living under a fluctuating climate and a drying Congo Basin. *Sustainability* 12:2936. doi: 10.3390/su12072936

Suárez Salazar, J. C., Casanoves, F., Ngo Bieng, M. A., Melgarejo, L. M., Di Rienzo, J. A., and Armas, C. (2021). Prediction model for sap flow in cacao trees under different radiation intensities in the western Colombian Amazon. *Sci. Rep*. 11, 1–13. doi: 10.1038/s41598-021-89876-z

Suárez Salazar, J. C., Melgarejo, L. M., Casanoves, F., Di Rienzo, J. A., Damatta, F. M., and Armas, C. (2018b). Photosynthesis limitations in cacao leaves under different agroforestry systems in the Colombian Amazon. *PLoS ONE* 13:e0206149. doi: 10.1371/journal.pone.0206149

Suárez Salazar, J. C., Ngo Bieng, M. A., Melgarejo, L. M., Di Rienzo, J. A., and Casanoves, F. (2018a). First typology of cacao (*Theobroma cacao* L.) systems in Colombian Amazonia, based on tree species richness, canopy structure and light availability. *PLoS ONE* 13:e0191003. doi: 10.1371/journal.pone.0191003

Thomas, E., Atkinson, R., Zavaleta, D., Rodriguez, C., Lastra, S., Arango, K., et al. (2023). The distribution of cadmium in soil and cacao beans in Peru. *Sci. Total Environ*. 881:163372. doi: 10.1016/j.scitotenv.2023.163372

Toledo-Hernández, M., Tscharntke, T., Tjoa, A., Anshary, A., Cyio, B., and Wanger, T. C. (2020). Hand pollination, not pesticides or fertilizers, increases cocoa yields and farmer income. *Agric. Ecosyst. Environ*. 304:107160. doi: 10.1016/j.agee.2020.107160

Tscharntke, T., Grass, I., Wanger, T. C., Westphal, C., and Batáry, P. (2022). Prioritise the most effective measures for biodiversity-friendly agriculture. *Trends Ecol. Evol.* 37, 397–398. doi: 10.1016/j.tree.2022.02.008

Vaast, P., and Somarriba, E. (2014). Trade-offs between crop intensification and ecosystem services: the role of agroforestry in cocoa cultivation. *Agroforest. Syst.* 88, 947–956. doi: 10.1007/s10457-014-9762-x

Wessel, M., and Quist-Wessel, P. F. (2015). Cocoa production in West Africa, a review and analysis of recent developments. *NJAS-Wageningen J. Life Sci.* 74, 1–7. doi: 10.1016/j.njas.2015.09.001

Wibaux, T., Konan, D.-C., Snoeck, D., Jagoret, P., and Bastide, P. (2017). Study of tree to tree yield variability among seedling-based cacao population in an industrial plantation in Cote D Ivore. *Exp. Agricult*. 54, 719–730. doi: 10.1017/S0014479717000345

Wiegel, J., Del Río Duque, M., Gutiérrez, J., Claros, L., Sanchez, D., Gómez, L., et al. (2020). *Coffee and Cacao Market Systems in the Americas: Opportunities for Supporting Renovation and Rehabilitation.* Cali: International Center for Tropical Agriculture (CIAT), 154.

World Cocoa Foundation (2022). *Cocoa Forest Initiative*. Available online at: https://worldcocoafoundation.org/programmes-and-initiatives/cocoa-and-forests-initiative (Accessed March 15, 2024).

Zu Ermgassen, E. K. H. J., Bastos Lima, M. G., Bellfield, H., Dontenville, A., Gardner, T., Godar, J., et al. (2022). Addressing indirect sourcing in zero deforestation commodity supply chains. *Sci. Adv.* 8:eabn3132. doi: 10.1126/sciadv.abn3132

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A methodological framework proposal for managing risk in small-scale farming through the integration of knowledge and data analytics

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Introduction: Climate change and weather variability pose significant challenges to small-scale crop production systems, increasing the frequency and intensity of extreme weather events. In this context, data modeling becomes a crucial tool for risk management and promotes producer resilience during losses caused by adverse weather events, particularly within agricultural insurance. However, data modeling requires access to available data representing production system conditions and external risk factors. One of the main problems in the agricultural sector, especially in small-scale farming, is data scarcity, which acts as a barrier to effectively addressing these issues. Data scarcity limits understanding the local-level impacts of climate change and the design of adaptation or mitigation strategies to manage adverse events, directly impacting production system productivity. Integrating knowledge into data modeling is a proposed strategy to address the issue of data scarcity. However, despite different mechanisms for knowledge representation, a methodological framework to integrate knowledge into data modeling is lacking.

Methods: This paper proposes developing a methodological framework (MF) to guide the characterization, extraction, representation, and integration of knowledge into data modeling, supporting the application of data solutions for small farmers. The development of the MF encompasses three phases. The first phase involves identifying the information underlying the MF. To achieve this, elements such as the type of knowledge managed in agriculture, data structure types, knowledge extraction methods, and knowledge representation methods were identified using the systematic review framework proposed by Kitchemhan, considering their limitations and the tools employed. In the second phase of MF construction, the gathered information was utilized to design the process modeling of the MF using the Business Process Model and Notation (BPMN). Finally, in the third phase of MF development, an evaluation was conducted using the expert weighting method.

Results: As a result, it was possible to theoretically verify that the proposed MF facilitates the integration of knowledge into data models. The MF serves as a foundation for establishing adaptation and mitigation strategies against adverse events stemming from climate variability and change in small-scale production systems, especially under conditions of data scarcity.

Discussion: The developed MF provides a structured approach to managing data scarcity in small-scale farming by effectively integrating knowledge into data modeling processes. This integration enhances the capacity to design and implement robust adaptation and mitigation strategies, thereby improving the resilience and productivity of small-scale crop production systems in the face of climate variability and change. Future research could focus on the practical application of this MF and its impact on small-scale farming practices, further validating its effectiveness and scalability.

KEYWORDS

methodological framework, small-scale farming, risk management, knowledge management, data modelling

1 Introduction

The development of agricultural insurance requires access to comprehensive data that accurately represents the conditions within productive systems and accounts for external risk factors. Currently, insurers employ techniques based on statistical and actuarial concepts to assess the conditions of the granted insurance and fulfill their acquired commitments. In this process, deficiencies in the mechanisms for determining insurance determinants are evident, stemming from a lack of understanding of the risk factors associated with agricultural activity and the vulnerability conditions of producers (Carter et al., 2017). Additionally, the non-stationary spatiotemporal structure of the data used for risk assessment introduces high complexity when a non-linear relationship between events and crop yield is present. Therefore, traditional statistical methods or other models may not be appropriate (Ghahari et al., 2019). By this, it is of great importance to propose alternatives that support the design of agricultural insurance, considering factors of data accessibility and availability in the agriculture domain.

At the farm level, crop yield data are either scarce or unavailable, impeding the estimation of individual losses due to a lack of representation and selection bias due to the high scarcity and low credibility of data at the local scale. Data scarcity can arise from the phenology of the assessed crops, as some have an extended development period, mainly perennial crops, making it challenging to obtain a historical data series. Additionally, in some productive systems, crop intercropping or rotation occurs, resulting in inconsistencies in data recording (Porth et al., 2019). Meanwhile, low credibility can be attributed to the fact that past data may not be representative of the current state of the productive system, owing to changes in management practices such as the use of technologies, application of agricultural inputs, and production arrangement, among others (Porth et al., 2014, 2019). These issues lead to the design of insurance being formulated based on regional or municipal data rather than local or farm scales, resulting in an aggregation bias. This bias may increase idiosyncratic risk by underestimating or overestimating the anticipated risk compared to the actual individual risk (Finger, 2012; Lyubchich et al., 2019), a situation known as base risk, one of the primary challenges associated with the design of agricultural insurance.

Base risk discourages producers from showing a low willingness to pay for agricultural insurance, owing to a lack of confidence in determining policy payments. In this regard, studies (Berg et al., 2009; Ramasubramanian, 2012; Thompson, 2017) evaluated the payment capability of producers, finding that they encounter issues with the insurance design, considering that payment is made based on an index constructed with data at the municipal or regional scale. Additionally, there are difficulties in comprehending the mechanisms for determining insurance policy payments. Therefore, it is pertinent to evaluate analytical methods that enhance the relationship between the indices determining policy payments and individual losses and increase transparency and trust in the methods employed to determine the proposed indices to improve their acquisition by producers.

Techniques based on machine learning, statistics, mechanistic or empirical models, or the integration of expert knowledge have been proposed to address the issue of base risk. Independently, each of these techniques presents drawbacks in its application. Mechanistic or empirical models have a high capacity to represent the complex processes of the agricultural system; however, their conception requires a high degree of knowledge of the system's processes, and their application necessitates specific input data for validation within new scenarios (Tartarini et al., 2021). Due to their high heterogeneity, statistical techniques have limitations when analyzing data with different structures, frequencies, and scales (Ghahari et al., 2019). On the other hand, machine learning techniques are constrained or yield inadequate results when insufficient data is available for training and validating the developed models or when their development or outcome lacks a rational explanation within the framework of natural laws or human regulation (Von Rueden et al., 2019; Roscher et al., 2020). Based on the preceding, there is a need to propose mechanisms that allow for mitigating the disadvantages presented by the individual application of techniques and to leverage the advantages each offers. Accordingly, this paper proposes a methodological framework (MF) to facilitate knowledge's characterization, extraction, representation, and integration into data modeling. This framework serves as a tool to support agricultural insurance design, particularly under data scarcity scenarios. The paper is structured as follows, the initial phase entails identifying the foundational information of the MF, employing the systematic review framework proposed by Kitchemhan (Kitchenham et al., 2009). The second phase of MF construction involves utilizing the gathered information to design the process model of the MF using the Business Process Model and Notation (BPMN; Chinosi and Trombetta, 2012). The third phase, involving an evaluation, was conducted employing the expert weighting method.

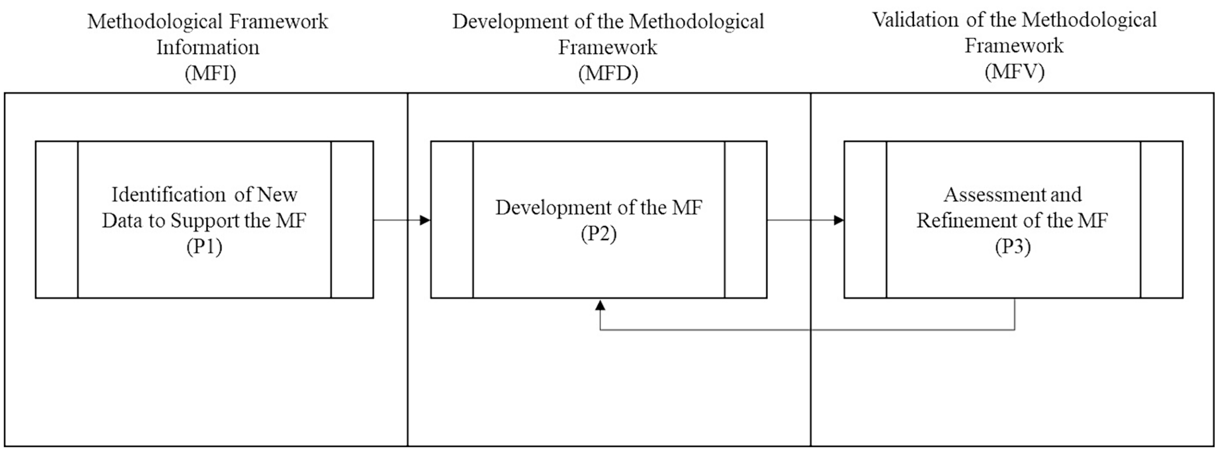

FIGURE 1
Phases and macro processes for the development of the methodological framework.

2 Materials and methods

A Methodological Framework (MF) provides the structure, elements, rules, and methods required to implement a particular process or a series of processes (McMeekin et al., 2020). Constructing an MF necessitates identifying data and information that underpin its development. In this regard, McMeekin et al. (2020) consolidates three phases from a literature review on MF development. The first phase corresponds to identifying evidence to inform the MF, initially considering the identification of utilized MFs, which will serve as the foundation for constructing the new framework. Secondly, unused data and information that aid in contextualizing the MF are identified. The second phase involves the development of the MF; in this phase, elements, processes, and techniques found in the recognized frameworks are adapted, combined, or complemented to structure the new framework.

Additionally, critical data identified in the second instance of phase one are extracted. The extracted information must be analyzed, synthesized, grouped, or merged into categories that will support the new MF, following an iterative approach until consensus is reached with experts, which will serve as a basis for refining the proposed framework. Finally, the third phase corresponds to the process of evaluating the MF.

In this regard, a macro-process is proposed for constructing an MF to support the implementation of agricultural insurance under a data scarcity scenario within the informed data analytics framework (Figure 1). The MF will consider the integration of different methodologies, which will be adapted within the guidelines proposed by McMeekin et al. (2020). The schematization of diagrams follows the procedures offered by the American National Standards Institute—ANSI (Zabinski, 2021).

In McMeekin et al. (2020), three (Porth et al., 2019) phases are established. The first corresponds to the identification of evidence to inform the MF (MFI), the second corresponds to the development of the MF (MFD), and the third corresponds to the evaluation and refinement of the MF (MFV). In MFI, one (Carter et al., 2017) macro-process is considered. It involves identifying new information supporting the new MF's development (P1). On the other hand, in MFD, one (Carter et al., 2017) macro-process is established, focused on the iterative development process of the MF (P2). Finally, in MFV, one (Carter et al., 2017) macro-process is found, oriented toward evaluating and refining the MF (P3).

2.1 Phase 1. Identification of new data to support the MF

To develop the macro-process (Figure 2), we consider the six steps for conducting a systematic review as established in the methodology proposed by Kitchenham (2004). The steps are the planning phase (SR-0), research identification (SR-1), primary study selection (SR-2), study quality assessment (SR-3), the relevant information is extracted from the preliminary studies (SR-4), and synthesis of the results found in the primary studies (SR-5). In the SR-0 phase, research questions and protocol design are established. In SR-1, the search strategy for the systematic review is generated, publication bias is identified, the bibliography management process is determined, and the search documentation mechanism is established. Additionally, in SR-2, inclusion and exclusion criteria are set for study selection. In SR-3, quality thresholds are defined, and instruments for their assessment are designed. In SR-4, relevant information is extracted from the primary studies; the formats established in the review planning are utilized to achieve this. Finally, in SR-5, a synthesis of the results found in the prior studies is carried out for a case study. The extracted information is tabulated in a way that consistently answers the research questions posed in the previous stages.

According to the review objectives, we present the plan to build that below.

2.1.1 PICOC

This study employs the PICOC framework (García-Peñalvo, 2022), with the population defined as the agriculture and knowledge domain. The review is specifically directed toward identifying the elements utilized in knowledge management within the agricultural sector. Furthermore, the primary emphasis lies in identifying

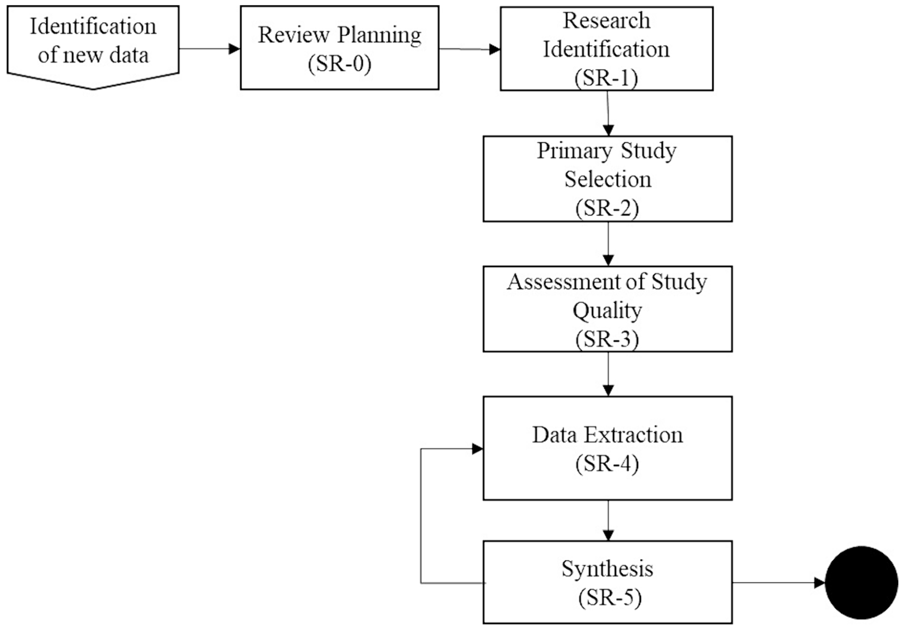

FIGURE 2
Illustrates the defined processes for the macro-process.

techniques, methods, and tools employed for extracting and representing knowledge. The "Comparison" component has not been considered, as there is no requirement for a specific comparison of the results obtained by applying identified methods or techniques.

- **Population**: Knowledge, agriculture
- **Intervention**: Methods or techniques for knowledge management
- **Outcome**: Describe methods or procedures for knowledge management in the field of agriculture
- **Context**: Systematic Review of methods or techniques for knowledge management in the field of agriculture

2.1.2 Research questions

Four research questions have been formulated, which are related to identifying the type of knowledge and data structure managed in knowledge management processes and identifying methods or techniques for knowledge extraction and representation in agriculture. Additionally, the identification of the most used tools for knowledge representation and the limitations of each recognized knowledge representation method have been addressed.

R1. What methods or techniques have been used to extract the different types of knowledge in agriculture?

R2. What methods or techniques have been used to represent knowledge in agriculture?

R3. What are the most commonly used techniques for knowledge extraction and representation?

R4. What are the main limitations posed by knowledge representation methods?

2.1.3 Keywords and synonyms

Following the procedural steps, keywords were chosen for the proposed research questions. These keywords will be instrumental in formulating search equations within bibliographic sources. The selected keywords encompass all types of activities undertaken in a knowledge management process.

Keyword	Synonyms
Agriculture	Agricultural
Knowledge	
Knowledge extraction	Knowledge discovery, Knowledge elicitation, Knowledge integration, Knowledge representation, knowledge acquisition, knowledge gathering, knowledge harvesting, knowledge revelation

2.1.4 Search string

An exploratory search equation was formulated, incorporating the critical term "agriculture" alongside all words associated with knowledge management processes. The equation was devised to address the review's posed questions. The search scope did not concentrate on the agricultural insurance domain, as a preliminary review indicated insufficient data retrieval to inform the Methodological Framework (MF; agricultur*) AND ("knowledge elicitation" OR "knowledge harvesting" OR "expertise extraction" OR "expertise elicitation" OR "knowledge discovery" OR "knowledge extraction" OR "knowledge acquisition" OR "knowledge gathering" OR "knowledge revelation" OR "knowledge representation" OR "knowledge integration") ≥ 2013.

2.1.5 Sources

The bibliographic sources IEEE, Scopus, and Web of Science are selected for their outstanding reputation and extensive coverage of scientific articles. The IEEE source is pivotal as it focuses explicitly on papers related to the engineering and data analytics component, providing a solid foundation for research in this field. On the other hand, Scopus and Web of Science span all knowledge areas, ensuring a comprehensive and multidisciplinary view of research. It is crucial for contextualizing and enriching the work, enabling the identification of interdisciplinary connections and emerging trends that may significantly contribute to the study at hand.

- IEEE[1]
- Scopus[2]
- WoS[3]

2.1.6 Selection criteria

About the selection criteria, consideration is given to studies that introduce new methods or replicate existing methods for knowledge extraction and representation. Additionally, studies corresponding to systematic reviews of the proposed topics are included, as they can provide comparative analyses or facilitate the identification of studies not captured by the formulated search equation. As for exclusion criteria, articles inaccessible through available databases are excluded, as some databases may have partial accessibility. Studies lacking descriptions of knowledge extraction or representation methods, those outside the domain of agriculture, and those lacking a clearly defined methodological and formal process are also excluded, as they lack a scientific foundation conducive to replication.

Inclusion Criteria:

- We select articles presenting novel methods or techniques for knowledge extraction or replicating existing ones.
- We choose research with new methods or techniques for knowledge representation or replicating existing ones.
- We pick papers incorporating a review as part of the research or where the review is the main objective.
- Finally, we sort out the most current version of an article in case of duplication across multiple sources.

We exclude papers:

- That is not accessible in the available databases.
- Outside the field of agriculture.
- That does not describe the required methods or techniques.
- The informal literature does not have a clearly defined research process.

2.1.7 Quality assessment checklist

In the quality evaluation process, criteria are considered to ensure that articles contain the necessary elements for the data extraction process. In this regard, articles that describe the methods or techniques for knowledge management (characterization, extraction, representation, and integration) are selected. These methods should not be solely based on expert opinions but should also offer sufficient information about the methodological process for obtaining the proposed results. The selected articles should also demonstrate that the methods or techniques used have been replicated in other studies or subjected to a rigorous evaluation. Furthermore, studies should acknowledge the limitations of the evaluated methods or approaches.

The established criteria are evaluated on a categorical scale, determining whether they fully, partially, or do not meet the specified criteria. Articles scoring equal to or above 4.0 are then chosen and proceed to the data extraction stage.

Questions:

- Is there a description of the methods or techniques for knowledge management?
- Are the results based on research rather than expert opinions?
- Do the articles provide sufficient information about the methodology and data used to develop or adapt the methods?
- Are the knowledge management methods presented in a practical case?
- Do the articles clearly state the limitations of the evaluated methods?

Answers:

- Yes
- Partially
- No

2.1.8 Data extraction form

Finally, to address the guiding questions of the review, the extraction of general information from the articles is considered to characterize the studies, such as the publication year and the specific application area within agriculture. Regarding the detailed required data, the type of data used in the analysis is considered to identify the handling of structured, unstructured, or semi-structured data. The kind of knowledge managed (explicit or implicit), the methods or techniques for knowledge extraction and representation, the tools (languages, software) used to apply methods, and the limitations identified in their application are also considered.

- Year
- Specific area of application
- Type of data used.
- Type of knowledge
- Extraction method or technique
- Representation method or technique
- Tools, languages, software
- Limitations

2.2 Phase 2. Development of the MF

Considering the information extracted, the development of the MF is constructed following the Business Process Notation and Modeling - BPMN. The Bizagi software (Bizagi, 2020) is employed to achieve this.

1 https://ieeexplore-ieee-org.ezproxy.unal.edu.co/
2 https://www-scopus-com.ezproxy.unal.edu.co/
3 https://www-webofscience-com.ezproxy.unal.edu.co/

2.3 Phase 3. Assessment and refinement of the MF

For the evaluation of the MF, the expert weighting method was employed, which considers the following steps under Ishizaka and Nemery (2013):

- Expert Identification: assembling a group of experts in knowledge application and its integration into data analytics processes, especially in agriculture.
- Definition of Evaluation Criteria: in this case, the following evaluation criteria were proposed, taking into consideration aspects of clarity and comprehensibility, relevance and pertinence, adaptability and flexibility, and feasibility of implementation:
    - C1: Is the Methodological Framework (MF) formulated and easily understandable for users and experts in data modeling?
    - C2: Does the MF adequately address challenges related to integrating knowledge in data modeling?
    - C3: Can the framework be adapted and applied in various data modeling contexts and situations?
    - C4: Is implementing and effectively implementing the MF in real-world settings feasible?
    - C5: Does the MF demonstrate activities related to characterization, extraction, and representation of knowledge?
    - C6: Are the potential advantages and benefits of applying the MF in the data modeling context identified?
    - C7: Does the MF address potential challenges that may arise during the knowledge management process in data modeling?
    - C8: Is it possible to consider adaptations or updates to the MF without compromising the overall proposed structure?
- Definition of the Evaluation Scale: a scale from 1 to 5 was used, where 1 indicates low acceptance, and 5 indicates high acceptance.
- Calculation of the Average: based on the evaluations provided by the experts, a total weighted score was determined for each criterion.
- Verification of Consensus: a review of significant discrepancies between the weights assigned by the experts was conducted. If substantial differences are found, reaching a consensus with the experts is necessary. For evaluating the consistency between experts, the Intraclass Correlation Coefficient (ICCa) and Spearman's coefficient were used. For the ICCa, the ranges established by Hills and Fleiss (1987) were considered (low if ICC < 0.40; good if 0.41 < ICC < 0.75; very good if ICC > 0.75). For Spearman's coefficient, the correlation between experts ranges from 0 to 1, with values close to 1 indicating higher correlation.
- Utilization of the Evaluation for Decision-Making: based on the conducted evaluation, a decision was made on whether the MF requires changes or if, on the contrary, it remains as initially established. It ensures an iterative process in the development of the MF.

3 Results

3.1 Identification of new data to support the MM

Applying the protocol outlined in Figure 2 and considering the elements established in the systematic review planning, articles about knowledge management in agriculture were assessed between 2013 and 2023. A total of 481 articles were initially identified, resulting in a final count of 37 articles after removing duplicates, applying the defined exclusion and inclusion criteria, and conducting a quality assessment of the studies (Figure 3). This structure conforms to the requirements for an indexed journal submission.

Following the data extraction process, various types of knowledge, extraction methods, representation methods, their limitations, central areas of application, and the tools employed were identified. Regarding knowledge representation methods, it was observed that 40.4% of the studies utilized knowledge graphs, followed by ontologies at 34.6% and production rules at 25% (Figure 4).

On the other hand, Table 1 identifies the techniques employed in the data extraction process, noting the utilization of manual procedures such as interviews or the application of surveys with experts, alongside Natural Language Processing (NLP) techniques oriented toward entity recognition and relation extraction in unstructured data. Some of the tools employed for knowledge extraction and representation were also identified. There was a notable prevalence of the "Web Ontology Language - OWL," used for knowledge representation in the Semantic Web, and the rule-oriented programming language CLIPS or one of its adaptations, such as Jess Rule, for knowledge representation through rules. Furthermore, in knowledge graphs, the Resource Description Framework (RDF) was identified as the primary means of representation. Additionally, the query language SPARQL was highlighted as essential for accessing and extracting information from RDF datasets.

Additionally, the main areas of intervention within the field of agriculture were identified, with pest and disease management accounting for 53.8%, comprehensive crop management at 19.2%, and nutritional management at 11.5% (Figure 5).

Regarding the data structure, 75% of the articles contemplate using unstructured data, encompassing text, images, audio, and video. 39% consider semi-structured data, and 12% pertain to structured data. Furthermore, the two types of knowledge considered in the knowledge management process were identified, with explicit knowledge comprising 92% of the studies and tacit knowledge accounting for 36% (Figure 6).

Finally, Table 2 presents some of the limitations of knowledge representation methods. At a general level, limitations were identified, such as the size of the knowledge base, the impact of the quality of input data on the reliability of the represented knowledge, the specificity of knowledge, which constrains its scalability, and the high requirement of experts for the creation and updating of the knowledge base. In ontologies, resistance may arise from formalizing specific agricultural domain knowledge, highlighting the challenge of representing knowledge with spatiotemporal characteristics.

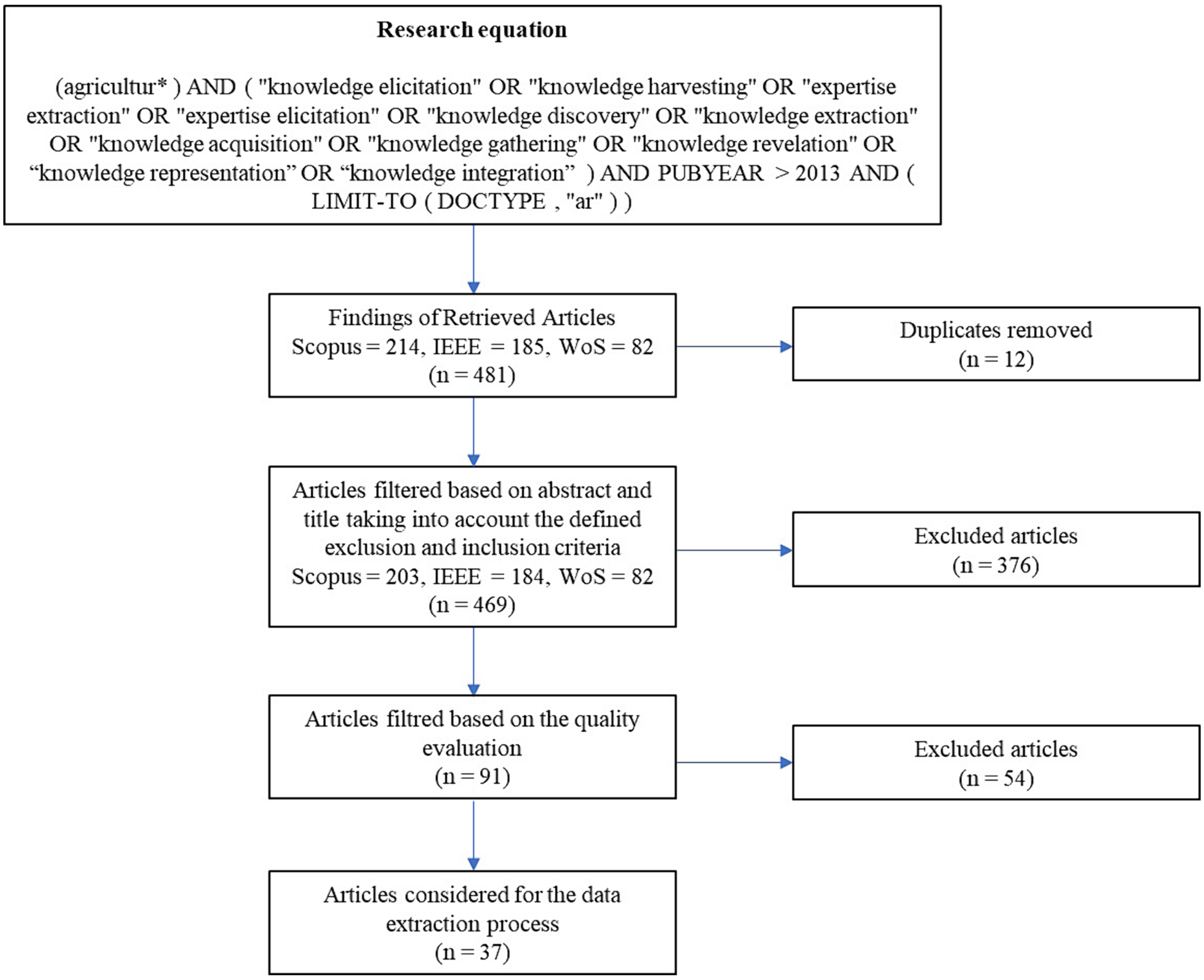

FIGURE 3
Systematic review process for identification of new data to support the MM.

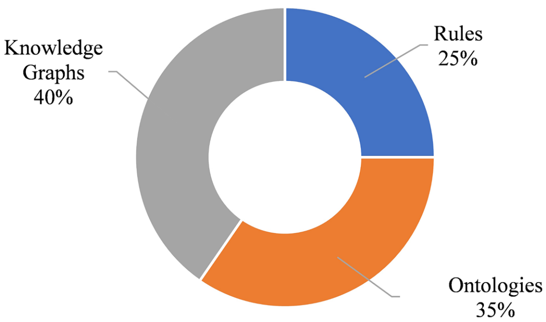

FIGURE 4
Knowledge representation distribution in the agriculture domain.

3.2 Development of the MF (P2)

Based on the information gathered during the systematic review process, the Knowledge Management Framework (MF) was proposed for subsequent integration into data analytics. Initially, the MF was proposed using the flow diagram standard, and subsequently, the refined process involved applying the Business Process Model and Notation (BPMN).

Knowledge Characterization and Knowledge Extraction (KC and KE): in the initial phase of the proposed MF, the characterization process of the data scarcity issue was considered, along with an assessment of the required knowledge type and the identification of available knowledge sources. These sources may contain either implicit or explicit knowledge. Therefore, a selection process was defined through a gate establishing an inclusive flow, meaning that both types may be found within the same knowledge source.

In cases where the source contains tacit knowledge, an elicitation process was outlined to extract unstructured data, which is subsequently stored in a data repository. Next, an activity was defined to extract implicit knowledge from the unstructured data, utilizing the identified extraction methods. These methods align with the Natural Language Processing techniques described in Table 1 and any others that may

TABLE 1 Extraction techniques and tools used.

Citations	Tools	Extraction techniques
Balleda et al. (2014)	CLIPS (C Language Integrated Production System)	–
Ahsan et al. (2014)	Protégé/OWL/RDF/SPARQL	–
Gaikwad et al. (2015)	LUCENE	–
Bonacin et al. (2016)	CMapTools/ yEd/ OWL/ RDF	Manual
Abbal et al. (2016)	GeNIe software, SMILE interface (Library)	Manual
Gomez-Perez et al. (2017)	GATE framework, Model View Controller, Apache Lucene, Spring MVC	Common Pattern Specification Language - CPSL
Kalita et al. (2017)	CLIPS (version 6.3), WxCLIPS	Manual
Devi and Dua (2017)	SPARQL/RDF/ Protégé	Stanford Dependency Trees
Agustina et al. (2017)	Prolog	–
Chenglin et al. (2018)	Neo4j, Cypher, RDF, and OWL	Named Entity Recognition (NER) Entity Disambiguation (Linking) Relation Extraction Segementation
Chatterjee et al. (2019)	–	Pattern recognition Text analysis Open information extraction Predicate-Argument Structure (PAS)
Ballot et al. (2018)	DEXi software	Manual
Stucky et al. (2018)	ELK Reasoner, OWL, OntoPilot, CyVerse, RDF	–
Xiaoxue et al. (2019)	Protégé/ TopBraid/ Composer/ WebProtege RDF/ OWL/ SPAQRL Stanford CoreNLP/ GATE Neo4j/ Virtuoso/ AllegroGrapf Stardog/ Ontotext/ PoolParty	Conditional Random Field (CRF) Syntactic Tree-based Relation Extraction
Yanchinda (2019)	CommonKADS	Manual
Aminu et al. (2019)	Protégé/ OWL2/ RDF	First-order logic (FOL)
Afzal and Kasi (2019)	SWRL (Semantic Web Rule Language) Jess Rule Reglas SWRL (Extensión de RDF)	
Malik et al. (2021)	OOPS! – OntOlogy Pitfall Scanner! / RDF	–
Jearanaiwongkul et al. (2019)	OWL	–
Goldstein et al. (2019)	OWL/ Protégé / RDF	–
Rousi et al. (2021)	DF/OWL (GeoTriples, RML y R2RML) - GraphDB (almacenamiento) - SPARQL (stSPAEQL - GeoSPARQL) y OWL2-RLR	–
Gharibi et al. (2020)	OWL, SPARQL, AGROVEC, ConceptNet API	POS tagging, chunking, and Stanford Parser
Godara and Toshniwal (2020)	–	Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS)
Kung et al. (2021)	SPARQL, TensorFlow	Lattice Long-Short-Term Memory (LSTM) Structured Perceptron, bidirectional Gated Recurrent Init (bi-GRU)

be placed. This process yields semi-structured or structured data. In the event of semi-structured data, a normalization and transformation process were established to convert it into structured data. Conversely, if the extraction yields structured data, it is directly stored in a data repository.

Finally, in cases where the assessed knowledge is explicit, the type of data structure to be processed was determined through an exclusive gate. Depending on the structure, the same processes defined earlier will be followed.

Knowledge Representation (KR): in the second phase, corresponding to the knowledge representation process, the selection of the knowledge representation method was defined. This decision was informed by the data repository containing the various representation methods and their respective limitations (Table 2). These limitations were

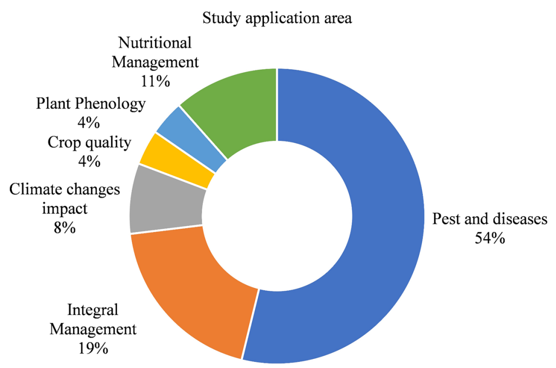

FIGURE 5
Study area application.

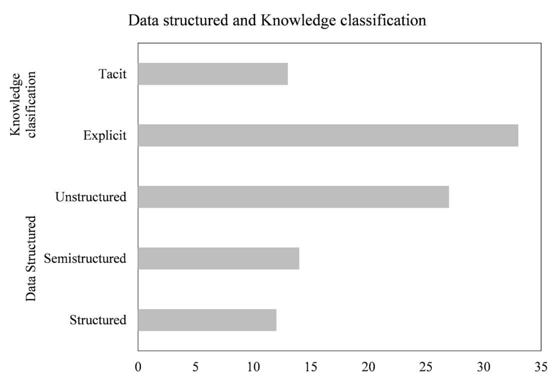

FIGURE 6
Data structured and knowledge classification.

identified for each method (Table 2). Subsequently, the representation method was implemented, considering the data object containing the available tools (Table 1). Following this, an exclusive gate was set up to evaluate the response of the knowledge representation method to the defined data scarcity issue. Should the implementation of the representation method appropriately address the problem, the represented knowledge is then stored in a data repository.

Knowledge Integration (KI): in the third phase of the MF, corresponding to the process of knowledge integration in data modeling, the task of integrating the knowledge represented in one or more phases of data modeling was established. This selection will depend on the model optimization objectives. This task makes use of the data warehouse containing the represented knowledge. Similarly, the knowledge integration process is defined by an inclusive gate, allowing the integration of knowledge in one or more phases simultaneously. In this sense, the represented knowledge can facilitate business or data understanding, support the data preparation process, optimize the modeling process, or support the evaluation process of the generated models. Following the model evaluation, compliance with the established requirements for the model was defined through an exclusive gate to proceed with its deployment or iterate the evaluation process of the integration phase(s).

Finally, in Figure 7, the Methodological Framework is presented, articulating the three phases that support the knowledge management process and its integration into data analytics models.

3.3 Assessment and refinement of the MF

In this phase of the MF development process, the framework underwent evaluation and refinement conducted by four experts in the field of data analytics. Eight evaluation criteria were employed, encompassing aspects of clarity and comprehensibility, relevance and pertinence, adaptability and flexibility, and feasibility of implementation.

o C1: Is the Methodological Framework (MF) formulated and easily understandable for users and experts in data modeling?
o C2: Does the MF adequately address challenges related to integrating knowledge in data modeling?
o C3: Can the framework be adapted and applied in various data modeling contexts and situations?
o C4: Is implementing and effectively putting the MF into practice in real-world settings feasible?
o C5: Does the MF demonstrate activities related to characterization, extraction, and representation of knowledge?
o C6: Are the potential advantages and benefits of applying the MF in the data modeling context identified?
o C7: Does the MF address potential challenges that may arise during the knowledge management process in data modeling?
o C8: Is it possible to consider adaptations or updates to the MF without compromising the overall proposed structure?

Following the evaluation conducted by experts (Figure 8), the highest weighted scores were assigned to criteria 3 (Lyubchich et al., 2019), 4 (4.4), 5 (4.4), and 8 (4.4), reflecting aspects of adaptability, flexibility, relevance, and reliability in implementation. On the other hand, criteria 1 (3.4), 2 (3.4), 6 (3.2), and 7 (3.8) yielded lower averages, although not falling below the mean evaluation level. These criteria are associated with the clarity, comprehensibility, and relevance of the Methodological Framework (MF). The lowest weighted score was attributed to criterion 6, which pertains to identifying the advantages and benefits of applying MF in data analytics. Furthermore, considering the indicators used to evaluate the consistency among experts, the ICCa was satisfactory, with a value of 0.41. Additionally, the average Spearman coefficient among all experts was 0.85, indicating a high level of concordance.

Furthermore, in addition to the assigned rating for each established criterion, the experts provided recommendations to be considered in addressing the weaknesses identified in the MF (Table 3).

Based on the consolidated information, modifications were made to the MF (Figure 9):

- Specific conditions were established at each output of the inclusive gateway for knowledge integration in data modeling, defining the objectives sought through the implementation of knowledge in data modeling.

TABLE 2 Limitations of knowledge representation methods.

Citations	Knowledge representation methods	Limitations
Balleda et al. (2014); Devraj and Deep (2015); Agustina et al. (2017); Gomez-Perez et al. (2017); Godara and Toshniwal (2020); Zhai et al. (2021); Nismi Mol and Santosh Kumar (2023)	Rules	• Knowledge Base Size • Metadata can be unreliable due to incomplete or incorrect information. • Their approach is specific to one domain and might not apply to others. • Incomplete meta-data may lead to unreliable knowledge. • Uncommon terms cause ambiguity in symptom description • Depends on helpline data quality, prone to errors and biases. • Rule-based models can be limited by the quality of the rules and the need for manual intervention to update the rules
Ahsan et al. (2014); Bonacin et al. (2016); Devi and Dua (2017); Chenglin et al. (2018); Stucky et al. (2018); Goldstein et al. (2019); Jearanaiwongkul et al. (2021); Malik et al. (2021); Rousi et al. (2021); Bhuyan et al. (2022)	Ontologies	• Meta-data may contain incomplete or incorrect information. • Certain agricultural knowledge types resist formalization using ontologies. • Results may vary based on data quality, keywords, and domain expertise. • Integration may encounter inconsistencies, errors, and missing data. • Ontology focuses on a specific domain. • The knowledge related may be insufficient. • Spatial–temporal knowledge representation is a challenge
Groumpos and Groumpos (2016); Yingying et al. (2017); Chenglin et al. (2018); Chatterjee et al. (2019); Xiaoxue et al. (2019); Gharibi et al. (2020); Kung et al. (2021)	Knowledge Graphs	• Meta-data may have unreliable, incomplete, or incorrect information. • Rules for diagnostic knowledge have limitations due to system complexity. • Meta-data can provide unreliable knowledge. • Method effectiveness varies across domains. • Annotated data is crucial for training. • Experts identify costly semantic relations • Tool quality depends on input knowledge. • Tool's performance is affected by input complexity

- A "data object" was added to describe various available methods for knowledge integration in data modeling.
- Stages of the knowledge management process were delimited and named using lanes.
- An activity was included to support the verification process of extracted tacit knowledge.
- The order for activities of knowledge characterization was reorganized.

4 Discussion

4.1 Knowledge characterization and extraction

The integration of knowledge into data modeling allows for a reduction in data dependence, an improvement in the precision and robustness of models, and, in some cases, confers physical meaning to the obtained results (Willard et al., 2020). Also, knowledge management strategies are critical for making decisions in climate change mitigations and adaptations to ensure better practices in small farming (Chisita and Fombad, 2020). In this context, some authors propose general frameworks for knowledge integration in data modeling, such as in Von Rueden et al. (2019), where the information flow in a process called informed machine learning is defined. This process generally involves problem identification and the search for a joint solution where data and prior knowledge are integrated, presenting some mechanisms for representing knowledge and its integration into data modeling. Similarly, in Roscher et al. (2020), an approach is proposed where the integration of domain knowledge is considered to improve the explainability of data models. Additionally, in Karpatne et al. (2017), despite not presenting a guide for knowledge management or its integration into data modeling, the paradigm of theory-guided data science is referred to, where the use of explicit and tacit knowledge is considered for refining the results of data models to be consistent with the understanding of physical phenomena.

Similarly, the proposed Methodological Framework (MF) is based on the general approach of integrating knowledge into data modeling. However, it delves into the processes by presenting specific activities to support the characterization, extraction, and representation of knowledge and its subsequent integration into data modeling. It considers the type of knowledge required, the type of data structure, and methods of knowledge extraction and representation, allowing for the support of the optimization of data models in their different development phases.

Regarding the characterization and extraction of knowledge, according to its origin and considering the types usually defined in the knowledge management area, it is classified as explicit and tacit knowledge (Hajric, 2018). Explicit knowledge, formalized and encoded, is called "Know-What." This type of knowledge is found in the content of indexed journals, databases, public documents, reports, videos, and images, among others. Explicit knowledge is contained in files with different formats of structure, known as structured, semi-structured, or unstructured data, and treated by various methods to carry out the extraction process. For the extraction process of explicit knowledge, the MF considers the identification of the type of data structure where it is contained. Data extraction and direct storage are proposed when dealing with structured formats, thinking they possess

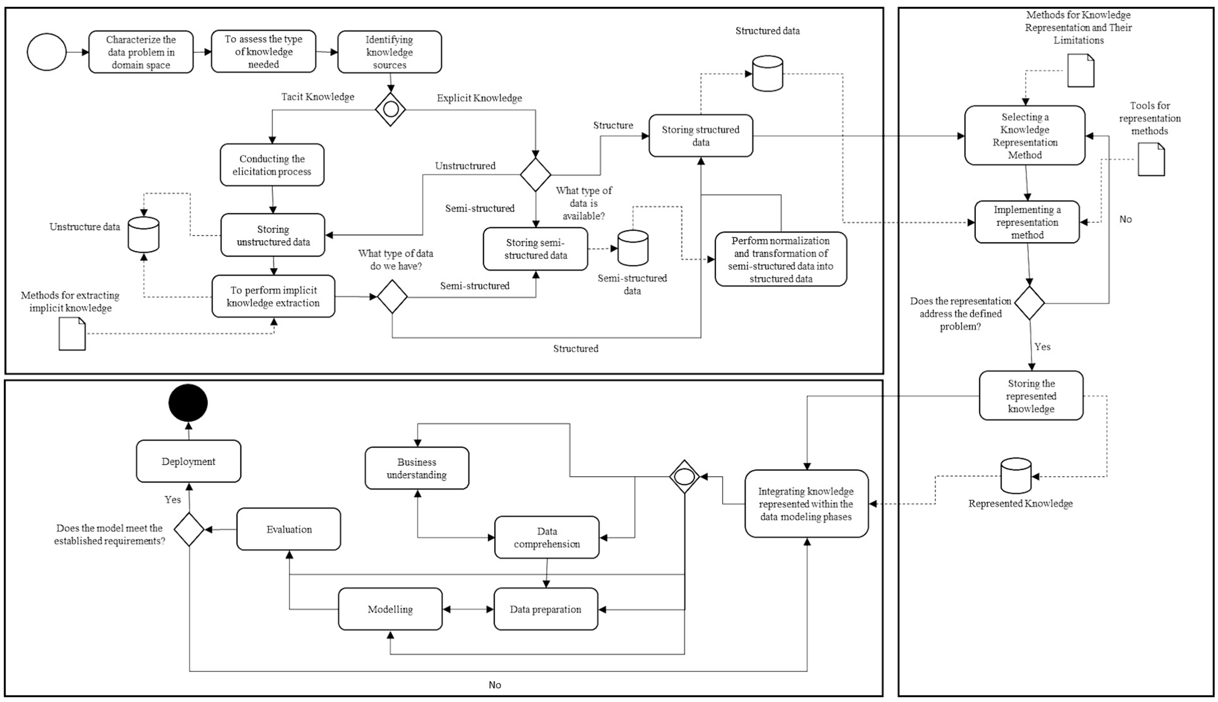

FIGURE 7
Methodological framework to support the integration of knowledge into data modeling under data scarcity scenarios.

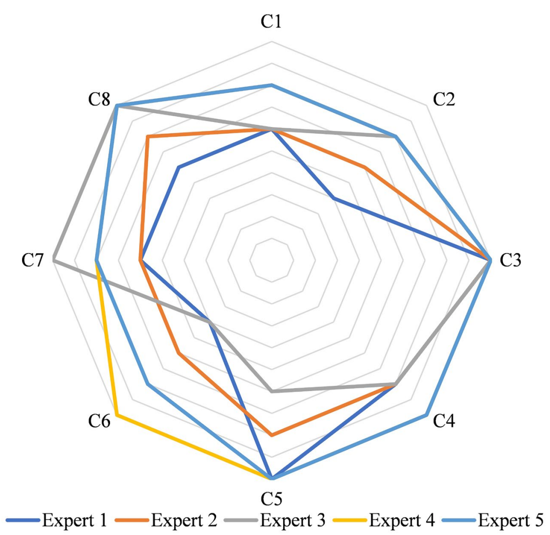

FIGURE 8
Methodological framework evaluation through expert weigh method.

TABLE 3 Expert recommendations to improve the MF.

Expert	Recommendations
1	The impact of knowledge on the dataset for modeling (data modification, variable selection, dataset creation) is not elucidated. It is essential to delineate the stages of knowledge management explicitly. Does the Methodological Framework (MF) exclusively address the issue of data scarcity, or does it also encompass other challenges where knowledge integration might prove beneficial?
2	It should be an extracted knowledge verification process.
4	Starting with the assumption that an organization is facing a data scarcity issue by characterizing the problem constrains the use cases of the Methodological Framework (MF). If "Identifying sources of knowledge" is addressed later, could the organization ascertain the data scarcity issue as early in the model? The pathways of knowledge integration into data modeling are not clearly understood.

a formal structure (Hajric, 2018). The performance of a normalization and transformation process from semi-structured to structured data is presented for semi-structured data. It is suggested by some authors who carry out the knowledge extraction process from HTML formats refined for the identification of concepts with the help of experts (Ahsan et al., 2014; Bonacin et al., 2016), the use of web crawlers to extract information directly from pages in HTML or XML formats (Baumgartner et al., 2005; Lin et al., 2018; Zhai et al., 2021) or the process of manual error correction, normalization, and standardization of semi-structured data to structured data suggested by Chenglin et al. (2018). This procedure is necessary to obtain data in a formal structure to be worked with using knowledge representation methods.

Similarly, tacit knowledge, known as "Know-How," corresponds to that found in the minds of individuals and has not been quantified or represented in any accessible format. It is manifested through practices and experiences in the application domain (Rhem, 2005; Becerra-Fernandez and Sabherwal, 2014) and possesses defining characteristics such as difficulty in communication, practicality, experiential nature, unconsciousness, and personalization (Pérez-Fuillerat et al., 2019). In the MF, when the process of extracting tacit knowledge is carried out, knowledge elicitation methods are used, which involve storing extracted knowledge from experts in non-structured formats (Jakus et al., 2013). The use of elicitation methods depends on the characteristics of the users with whom the process will be developed. In the case of agriculture, some studies suggest the application of techniques such as knowledge harvesting (Frappaolo, 2008), storytelling (Whyte and Classen, 2012; Prasarnphanich et al., 2016; Zammit et al., 2018), interviews (Ferrari et al., 2016), and video sharing (Zammit et al., 2018).

Subsequently, when knowledge is contained in a non-structured data format, either through elicitation or explicit knowledge in this structure, the MF proposes a process of extracting knowledge considered implicit knowledge. It refers to patterns or relationships between data that are not evident to humans (Frappaolo, 2008). For this purpose, a tacit knowledge extraction task is established and supported by a data object containing extraction methods identified in the agriculture domain. Among the recognized methods, some studies report the use of manual tasks to carry out the extraction and categorization of data (Devraj and Deep, 2015; Bonacin et al., 2016; Goldstein et al., 2019; Admass, 2022). Similarly, some authors mention Natural Language Processing (NLP) techniques, such as the "Stanford Dependency Trees" structure used for extracting entities from the agricultural knowledge domain (Devi and Dua, 2017), Named Entity Recognition (NER) used for identifying and classifying entities from text into predefined categories (Chenglin et al., 2018), Predicate-Argument Structure (PAS) used to represent relationships between the predicate and its arguments (nouns, prepositional phrases, etc.) in a sentence (Chatterjee et al., 2019), Conditional Random Field (CRF), which corresponds to a probabilistic graphical model used for sequence labeling, and Syntactic Tree-based Relation Extraction, which uses syntactic trees to extract relationships between named entities in text (Xiaoxue et al., 2019). There are also tasks proposed by Gharibi et al. (2020), such as POS tagging, chunking, and Stanford Parser, which allow the identification of relevant words, their grouping into meaningful phrases, and the provision of a syntactic structure for understanding relationships between words. Finally, other authors mention the use of neural networks such as Lattice Long Short-Term Memory (LSTM), Structured Perceptron, or Bidirectional Gated Recurrent Init (bi-GRU; Kung et al., 2021; Zhu et al., 2021), used to process sequences of data in texts. These methods are necessary to identify patterns that are not explicit to humans and are present in the unstructured data used in the knowledge characterization process.

4.2 Knowledge representation

On the other hand, following Bergman (2018), knowledge representation is the description of an object through different elements. Knowledge representation comprises three main aspects: concepts as basic units of knowledge, associations or relationships between concepts, and a dynamic structure built by the concepts and their associations (Gutiérrez, 2012). Knowledge representation methods are applied to logical language resources, that is, formal and explicit language. Therefore, the Methodological Framework (MF) establishes a series of activities to extract and transform knowledge from unstructured and semi-structured data into a set of structured data that possess the required characteristics to implement representation methods (Staab and Studer, 2009). In this context, the MF delineates activities for selecting the knowledge representation method and its subsequent implementation. It is supported by data objects containing representation methods, their limitations, and the tools available to carry out the process.

The methods identified are production rules, generally used for procedural knowledge representation (Yingying et al., 2017), i.e., methods or processes for performing a task (Gutiérrez, 2012). In agriculture, it has been widely used, especially for supporting pest and disease management (Balleda et al., 2014; Devraj and Deep, 2015; Kalita et al., 2017; Yingying et al., 2017; Admass, 2022). In some cases, production rules are used with other knowledge representation methods, as in Yingying et al. (2017), where rules are combined with knowledge graphs to design an expression and reasoning model for diagnosing diseases in tomato cultivation. In Afzal and Kasi (2019), a knowledge model based on ontology was developed to support rice production, using rules to keep the reasoning process of the knowledge base created through ontology. Additionally, in Sottocornola et al. (2023), rules are employed to support the explanation process of diagnosis in treating diseases in apple cultivation.

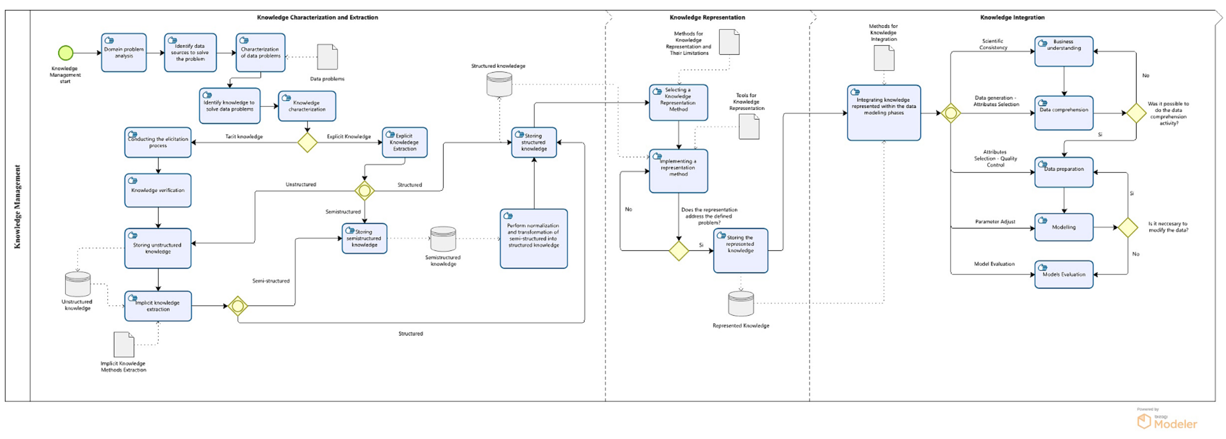

FIGURE 9
Methodological framework for knowledge characterization, extraction, representation and integration into data modeling.

However, the use of production rules in agriculture has limitations, such as the relatively small size of the constructed knowledge bases (Balleda et al., 2014); moreover, when working with semi-structured or unstructured data, metadata may be derived from unreliable sources due to incomplete or incorrect information (Gomez-Perez et al., 2017). Rule-based systems are limited to the dataset used for constructing the knowledge base, which may not represent all the dynamics of the addressed problem (Godara and Toshniwal, 2020). Similarly, rule-based models are limited by the quality of the rules and require extensive expert intervention in the domain for rule maintenance and updating. They also face challenges when attempting to scale to other problems, either within the same domain or outside of it (Nismi Mol and Santosh Kumar, 2023).

On the other hand, ontologies can be defined as a formal and explicit specification of a set of related concepts (Jakus et al., 2013). Some studies in agriculture have proposed the use of ontologies to improve semantic interoperability between developed systems and data sources (Bonacin et al., 2016; Stucky et al., 2018), design and build a knowledge base to support query systems (Devi and Dua, 2017; Aminu et al., 2019; Jearanaiwongkul et al., 2019), support the development of knowledge graphs serving as a design layer (Chenglin et al., 2018; Xiaoxue et al., 2019), provide lexical modeling and conceptualization to extracted knowledge (Yanchinda, 2019) or propose a semantic representation of IoT device data to reduce the need for human intervention (Afzal and Kasi, 2019). However, ontologies have limitations in their application, such as linguistic disambiguation. Expert keyword selection and query formulation may affect the quality of results, requiring a high availability of experts for any system scaling process. Many resources are needed for knowledge base maintenance.

Additionally, there is a low standardization of concepts in the agriculture domain, affecting ontology understanding and consistency, along with language barriers in which concepts used for ontology construction are found (Ahsan et al., 2014; Bonacin et al., 2016; Goldstein et al., 2019; Fahad et al., 2021; Kung et al., 2021; Malik et al., 2021). These limitations have led to the development of graphs as a novel mechanism for knowledge representation. It involves the extraction of entities, attributes, and their relationships, integrating knowledge through entity alignment and association with ontologies. Moreover, it facilitates the completion of the knowledge update and retrieval processes (Xiaoxue et al., 2019).

Like ontologies, knowledge graphs serve as a structured semantic knowledge base that describes concepts and their relationships in symbols (Xiaoxue et al., 2019). In this sense, graphs can be represented with varying levels of formalization, depending on whether one desires a lighter and more flexible representation or aims for knowledge representation with semantic consistency, integrating with an ontology that serves as a design layer for the knowledge graph (Chenglin et al., 2018). Under this, some authors have proposed the use of knowledge graphs with semantic support through ontologies to assess the impacts of agriculture and climate change on water resources (Bonacin et al., 2016), represent knowledge at a general level in the agricultural field (Ahsan et al., 2014; Devi and Dua, 2017; Chatterjee et al., 2019; Malik et al., 2021), automatically generate agrometeorological reports (Chenglin et al., 2018), address fertilization and soil management in corn cultivation (Aminu et al., 2019), support decision-making in pest and disease management (Goldstein et al., 2019; Jearanaiwongkul et al., 2021), and precision agriculture (Fahad et al., 2021).

Similarly, studies have been proposed to consider using knowledge graphs to support the wine sector, employing a lighter and more flexible representation, i.e., without being supported by an ontology (Abbal et al., 2016; Groumpos and Groumpos, 2016). Finally, like ontologies and production rules, knowledge graphs present similar limitations, such as low scalability to other knowledge domains and even to different areas within the same knowledge domain. The quality of the represented knowledge depends on the input data to the system (Chenglin et al., 2018), the need for labeled data for the application of machine learning models for entity and relationship extraction, and the necessity of domain knowledge experts for identifying or verifying meaningful semantic relationships among extracted concepts, which can consume significant resources (Chatterjee et al., 2019); moreover, graphs must undergo constant maintenance and updates, requiring a substantial allocation of resources due to the need for a high level of expertise in the knowledge domain (Xiaoxue et al., 2019). When selecting a knowledge representation method, the limitations of its application must be considered to address the problem appropriately.

4.3 Knowledge integration

Integrating knowledge into data modeling is of great interest, particularly in scenarios where data might be inaccessible, unavailable, or of low quality (Porth et al., 2019). Knowledge integration can occur at any phase of modeling (Von Rueden et al., 2023). Therefore, within the MF (Methodological Framework), a flow is established through an inclusive gate that allows the inclusion of knowledge represented in any data modeling phase. The conditions set in the inclusive gate include data generation (data understanding), model evaluation (model assessment), parameter adjustment (model development), scientific consistency (business understanding and model evaluation), and attribute selection (data preparation). In this regard, studies have been proposed related to knowledge integration in the data acquisition phase (Hain et al., 2011; Wang et al., 2017; Read et al., 2019; Yu et al., 2019; Clemens and Viechtbauer-Gruber, 2020; Downton et al., 2020; Zhao et al., 2020; Sepe et al., 2021; Yu et al., 2021; Raymond et al., 2022; Schröder et al., 2022), data preparation phase (Froehlich, 2020; Mudunuru and Karra, 2021; Bajracharya and Jain, 2022; Fuhg and Bouklas, 2022; Kohtz et al., 2022), optimization process of machine learning algorithms (Anoop Krishnan et al., 2018; Azari et al., 2020; Chadalawada et al., 2020; Huang et al., 2020; Qian et al., 2020; Sun et al., 2020; Tartakovsky et al., 2020; Jurj et al., 2021; Lu et al., 2021; Soriano et al., 2021; Kim et al., 2022), and as support for explaining data model results (MacInnes et al., 2010; Read et al., 2019).

Ontologies and knowledge graphs can support interoperability among knowledge domain datasets, verify the quality of extracted data, classify data, extract attributes or relationships, or facilitate working with heterogeneous data (Robinson and Haendel, 2020; Sahoo et al., 2022; Mummigatti et al., 2023). Furthermore, axioms established in an ontology can support constructing new ontologies by inducing the reuse of existing knowledge or verifying the consistency of the new ontology (Smith et al., 2007; Mungall et al., 2011). They can also expand or enrich the characteristics used in a machine learning model without finding relationships from the data, ensuring consistency or coherence through context rules (Kulmanov et al., 2021; Shrivastava and Deepak, 2023). Similarly, ontologies and graphs can be used for task prediction (Mazandu et al., 2017; Chen et al., 2021), text clustering (Wei et al., 2015; Ruas and Grosky, 2018; Mehta et al., 2021), or to support attribute reduction or selection (Garla and Brandt, 2012). These integrations are typically achieved through entity similarity or embedded entity methods (Deepa and Vigneshwari, 2019; Sun et al., 2020; Mežnar et al., 2022). Therefore, ontologies and knowledge graphs are highly useful in supporting the development of data models, especially in contexts such as small-scale agriculture, where historical data series are mostly unavailable, or the available data is of low quality.

On the other hand, in some cases, knowledge can be explicitly represented, allowing its integration into data modeling phases without any characterization or extraction process. In this regard, hybrid models that integrate results from mechanistic or empirical models have been developed, either for generating training data or for model evaluation data (Ji and Lu, 2018; Feng et al., 2019; Maya Gopal and Bhargavi, 2019; Saha et al., 2020; Sansana et al., 2021). Additionally, the integration of algebraic or differential equations has been proposed, which can be used to condition policy in learning, modify the error function, function parameterization, or as restrictive functions (Mangasarian and Wild, 2008; Karpatne et al., 2017; Lu et al., 2017; Muralidhar et al., 2019; Ramamurthy et al., 2019; Asvatourian et al., 2020; Gupta and Das, 2020; Meng et al., 2022). Similarly, invariance properties have been proposed to enhance the performance of machine learning models (Ling et al., 2016; Wu et al., 2018). Lastly, expert knowledge has been incorporated to ensure that results generated by machine learning models have scientific consistency (Brown et al., 2012; Choo et al., 2013; Spinner et al., 2020). Thus, knowledge integration depends on the improvement objectives sought concerning data models.

4.4 The methodological framework as a tool for risk management in small-scale farming

The increase in variability and climate change, diseases, and pests, among other problems, negatively impacts agriculture, particularly affecting small-scale producers who are highly vulnerable and have low resilience. Additionally, food security relies on the adaptive capacity of small-scale producers to address such events (Hatfield et al., 2020). A significant amount of research has proposed data methods to contribute to solving these problems (Xie, 2011; Ghahari et al., 2019) (Dalhaus et al., 2018; Wang et al., 2018; Mangani and Kousalya, 2019; Roznik et al., 2019; Shirsath et al., 2019; Boyd et al., 2020; Zhang et al., 2020). However, the information used has different temporal and spatial resolution, affecting its correct application at the local level. At the local level, farmers possess knowledge about practices and techniques; however, this local knowledge can vary from one agricultural region to another. In this context, knowledge extraction and representation can be useful for storing knowledge from heterogeneous sources and sharing it with farmers (Jearanaiwongkul et al., 2019; Haider et al., 2021). Furthermore, there is an exponential amount of data about farm management and system conditions, necessitating proper methods to represent and share this data to support farmers' activities (Aminu et al., 2019; Goldstein et al., 2019; Bhuyan et al., 2022). For this reason, in the context of small-scale farming, it is necessary to complement data analysis with knowledge that can support model development, considering data scarcity and heterogeneity.

Another problem where the Framework can be useful is addressing the lack of financial data to support risk management in the context of financial inclusion. In this sense, knowledge about system conditions or agronomic management may be necessary for develop new instruments for improvement. The Methodological Framework (MF) can facilitate the extraction and representation of knowledge from various sources to build new tools, such as credit scoring, while considering the heterogeneity of diverse agricultural systems (Simumba et al., 2018; Bunnell et al., 2021).

In the context of agricultural insurance, the management and integration of knowledge in data modeling will enable the proposition of agricultural insurance design solutions, facilitating the reduction of aggregation bias by considering specific characteristics of the production system. These include crop phenology, access conditions or availability of primary resources and implementing techniques or practices that enhance or diminish producers' adaptive capacity. Additionally, it may facilitate the integration of area-related knowledge, such as agroecological classifications or soil types. This adjustment would fine-tune the utilization of the proposed parametric index, consequently mitigating idiosyncratic risks. It also aims to minimize gaps in insurance acquisition stemming from poor design comprehension or a weak correlation between premium payments and individual-level losses (Berg et al., 2009; Ramasubramanian, 2012; Thompson, 2017; Fonta et al., 2018; Madaki et al., 2023).

The optimization of data models through knowledge can provide producers with more adaptive tools to enhance their resilience against variability and climate change events, diseases, pest control, and all agronomic management factors contributing to food security and economic growth in small-scale agriculture.

5 Conclusion and recommendations

The Methodological Framework (MF) is a tool designed to guide researchers in knowledge management. It defines techniques and methods for knowledge characterization, extraction, representation, and integration into data modeling to support data model development, particularly in risk management in small-scale agriculture. One of the main challenges in knowledge representation is that knowledge can be specific to one domain and might not apply to others. Therefore, it is essential to increase research on methods for data interoperability and knowledge sharing and evaluate reasoning characteristics.

Additionally, it is crucial to continue research on techniques for knowledge extraction, considering the significant amount of heterogeneous data and information sources (such as images, text, audio, and video) that can support development in the agricultural sector. Particular attention should be given to methods or techniques used for knowledge extraction from unstructured data.

It should be noted that the Methodological Framework (MF) was evaluated through an expert consensus. For this reason, it is considered a proposal, and it is crucial to apply the framework to address problems in small-scale farming, especially when there is a significant lack of consistent and high-quality data available. An example of such application is the design of agricultural insurance in small-scale farming, with an emphasis on the processes of index selection, data preparation, and determination of optimal triggers, exit thresholds, and premium calculation.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

JCA: Conceptualization, Methodology, Writing – original draft, Writing – review & editing. JCO: Conceptualization, Writing – review & editing.

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Conflict of interest

JCA was employed by the company Ecotecma S.A.S.

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References

Abbal, P., Sablayrolles, J. M., Matzner-Lober, É., Boursiquot, J. M., Baudrit, C., and Carbonneau, A. (2016). A decision support system for vine growers based on a Bayesian network. *J. Agric. Biol. Environ. Stat.* 21, 131–151. doi: 10.1007/s13253-015-0233-2

Admass, W. S. (2022). Developing knowledge-based system for the diagnosis and treatment of mango pests using data mining techniques. *Int. J. Inf. Technol.* 14, 1495–1504. doi: 10.1007/s41870-022-00870-8

Afzal, H, and Kasi, MK. Ontology-based knowledge modeling for rice crop production. In: *Proceedings - 2019 international conference on future internet of things and cloud, FiCloud 2019*. (2019).

Agustina, E, Pratomo, I, Wibawa, AD, and Rahayu, S. Expert system for diagnosis pests and diseases of the rice plant using forward chaining and certainty factor method. In: *2017 international seminar on intelligent technology and its application: Strengthening the link between university research and industry to support ASEAN energy sector, ISITIA 2017 - proceeding*. (2017).

Ahsan, M, Motla, YH, and Asim, M. Knowledge modeling fore-agriculture using ontology. In: *ICOSST 2014–2014 international conference on open source systems and technologies, proceedings*. (2014).

Aminu, EF, Oyefolahan, IO, Abdullahi, MB, and Salaudeen, MT. An OWL based ontology model for soils and fertilizations knowledge on maize crop farming: scenario for developing intelligent systems. In: 2019 *15th international conference on electronics, Computer and Computation, ICECCO* (2019). 2019.

Anoop Krishnan, N. M., Mangalathu, S., Smedskjaer, M. M., Tandia, A., Burton, H., and Bauchy, M. (2018). Predicting the dissolution kinetics of silicate glasses using machine learning. *J. Non-Cryst. Solids* 487, 37–45. doi: 10.1016/j.jnoncrysol.2018.02.023

Asvatourian, V., Leray, P., Michiels, S., and Lanoy, E. (2020). Integrating expert's knowledge constraint of time dependent exposures in structure learning for Bayesian networks. *Artif. Intell. Med.* 107:101874. doi: 10.1016/j.artmed.2020.101874

Azari, A. R., Lockhart, J. W., Liemohn, M. W., and Jia, X. (2020). Incorporating physical knowledge into machine learning for planetary space physics. *Front. Astronomy Space Sci.* 7:7. doi: 10.3389/fspas.2020.00036

Bajracharya, P., and Jain, S. (2022). Hydrologic similarity based on width function and hypsometry: An unsupervised learning approach. *Comput. Geosci.* 163:105097. doi: 10.1016/j.cageo.2022.105097

Balleda, K, Satyanvesh, D, NVSSP, Sampath, KTN, Varma, and Baruah, PK. Agpest: An efficient rule-based expert system to prevent pest diseases of rice & wheat crops. In: *2014 IEEE 8th international conference on intelligent systems and control: Green challenges and smart solutions, ISCO 2014 - proceedings*. (2014).

Ballot, R., Loyce, C., Jeuffroy, M. H., Ronceux, A., Gombert, J., Lesur-Dumoulin, C., et al. (2018). First cropping system model based on expert-knowledge parameterization. *Agron. Sustain. Dev.* 38:33. doi: 10.1007/s13593-018-0512-8

Baumgartner, R, Frölich, O, Gottlob, G, Herzog, M, and Lehmann, P. Integrating semi-structured data into business applications: a web intelligence example. In: Lecture notes in computer science (including subseries lecture notes in artificial intelligence and lecture notes in bioinformatics). (2005).

Becerra-Fernandez, I., and Sabherwal, R. (2014). Knowledge management: systems and processes. 2nd Edn, (New York: Routledge), p. 382.

Berg, A., Quirion, P., and Sultan, B. (2009). Weather-index drought insurance in Burkina-Faso: assessment of its potential interest to farmers. *Weather, Climate, and Society.* 1, 71–84. doi: 10.1175/2009WCAS1008.1

Bergman, MK. (2018). A Knowledge Representation Practionary. Switzerland, AG: Springer Cham.

Bhuyan, B. P., Tomar, R., and Cherif, A. R. (2022). A systematic review of knowledge representation techniques in smart agriculture (urban). *Sustainability (Switzerland).* 14, 1049–1055. doi: 10.3390/su142215249

Bizagi, . Bizagi Modeler User Guide. (2020).

Bonacin, R.Nabuco OF, and Pierozzi, J. I. (2016). Ontology models of the impacts of agriculture and climate changes on water resources: scenarios on interoperability and information recovery. *Futur. Gener. Comput. Syst.* 54, 423–434. doi: 10.1016/j.future.2015.04.010

Boyd, M., Porth, B., Porth, L., Seng Tan, K., Wang, S., and Zhu, W. (2020). The Design of Weather Index Insurance Using Principal Component Regression and Partial Least Squares Regression: the case of forage crops. *North American Actuarial J.* 24, 355–369. doi: 10.1080/10920277.2019.1669055

Brown, ET, Liu, J, Brodley, CE, and Chang, R. Dis-function: learning distance functions interactively. In: *IEEE conference on visual analytics science and technology 2012, VAST 2012 - proceedings*. (2012).

Bunnell, L., Osei-Bryson, K. M., and Yoon, V. Y. (2021). Development of a consumer financial goals ontology for use with FinTech applications for improving financial capability. *Expert Syst. Appl.* 165:113843. doi: 10.1016/j.eswa.2020.113843

Carter, M., De Janvry, A., Sadoulet, E., and Sarris, A. (2017). Index Insurance for Developing Country Agriculture: a reassessment. *Ann. Rev. Resour. Econ.* 9, 421–438. doi: 10.1146/annurev-resource-100516-053352

Chadalawada, J., Herath, H. M. V. V., and Babovic, V. (2020). Hydrologically informed machine learning for rainfall-runoff modeling: a genetic programming-based toolkit for automatic model induction. *Water Resour. Res.* 56, 1430–1436. doi: 10.1029/2019WR026933

Chatterjee, N., Kaushik, N., and Bansal, B. (2019). Inter-subdomain relation extraction for agriculture domain. *IETE Techn. Rev. (Institution of Electronics and Telecommun. Engineers, India).* 36, 157–163. doi: 10.1080/02564602.2018.1435312

Chen, J., Althagafi, A., and Hoehndorf, R. (2021). Predicting candidate genes from phenotypes, functions and anatomical site of expression. *Bioinformatics* 37, 853–860. doi: 10.1093/bioinformatics/btaa879

Chenglin, Q, Qing, S, Pengzhou, Z, and Hui, Y. (2018). Cn-MAKG: China meteorology and agriculture knowledge graph construction based on semi-structured data. In: Proceedings - *17th IEEE/ACIS international conference on computer and information science*, ICIS 2018.

Chinosi, M., and Trombetta, A. (2012). BPMN: An introduction to the standard. *Comput Stand Interfaces.* 34, 124–134. doi: 10.1016/j.csi.2011.06.002

Chisita, C. T., and Fombad, M. (2020). Knowledge Management for Climate Change Adaptation to enhance urban agriculture among selected Organisations in Zimbabwe. *J. Inf. Knowl. Manag.* 19:2050009. doi: 10.1142/S0219649220500094

Choo, J., Lee, C., Reddy, C. K., and Park, H. (2013). UTOPIAN: user-driven topic modeling based on interactive nonnegative matrix factorization. *IEEE Trans. Vis. Comput. Graph.* 19, 1992–2001. doi: 10.1109/TVCG.2013.212

Clemens, T., and Viechtbauer-Gruber, M. (2020). Impact of digitalization on the way of working and skills development in hydrocarbon production forecasting and project decision analysis. *SPE Reserv. Eval. Eng.* 23, 1358–1372. doi: 10.2118/200540-PA

Dalhaus, T., Musshoff, O., and Finger, R. (2018). Phenology information contributes to reduce temporal basis risk in agricultural weather index insurance. *Sci. Rep.* 8:46. doi: 10.1038/s41598-017-18656-5

Deepa, R., and Vigneshwari, S. (2019). A novel HNN-DOC for automated agricultural ontology construction on climate factors. *Int. J. Recent Technol. Engineer.* 8, 6040–6042. doi: 10.35940/ijrte.C5586.098319

Devi, M, and Dua, M. ADANS: An agriculture domain question answering system using ontologies. In: *Proceeding - IEEE international conference on computing, Communication and Automation, ICCCA*. (2017). 2017.

Devraj, Jain R, and Deep, V. Expert system for the management of insect-pests in pulse crops. In: *2015 international conference on computing for sustainable global development, INDIACom 2015*. (2015).

Downton, J. E., Collet, O., Hampson, D. P., and Colwell, T. (2020). Theory-guided data science-based reservoir prediction of a North Sea oil field. *Lead. Edge* 39, 742–750. doi: 10.1190/tle39100742.1

Fahad, M., Javid, T., Beenish, H., Siddiqui, A. A., and Ahmed, G. (2021). Extending ONTAgri with service-oriented architecture towards precision farming application. *Sustainability (Switzerland).* 13:9801. doi: 10.3390/su13179801

Feng, P., Wang, B., Liu, D. L., Waters, C., and Yu, Q. (2019). Incorporating machine learning with biophysical model can improve the evaluation of climate extremes impacts on wheat yield in South-Eastern Australia. *Agric. For. Meteorol.* 275, 100–113. doi: 10.1016/j.agrformet.2019.05.018

Ferrari, A., Spoletini, P., and Gnesi, S. (2016). Ambiguity and tacit knowledge in requirements elicitation interviews. *Requir. Eng.* 21, 333–355. doi: 10.1007/s00766-016-0249-3

Finger, R. (2012). Biases in farm-level yield risk analysis due to data aggregation. *German J. Agric. Econ.* 61, 30–43.

Fonta, W. M., Sanfo, S., Kedir, A. M., and Thiam, D. R. (2018). Estimating farmers' willingness to pay for weather index-based crop insurance uptake in West Africa: insight from a pilot initiative in southwestern Burkina Faso. *Agric. Food Econ.* 6, 1531–1532. doi: 10.1186/s40100-018-0104-6

Frappaolo, C. (2008). Implicit knowledge. *Knowl. Manag. Res. Pract.* 6, 23–25. doi: 10.1057/palgrave.kmrp.8500168

Froehlich, D. C. (2020). Neural network prediction of alluvial stream Bedforms. *J. Hydraul. Eng.* 146. doi: 10.1061/(ASCE)HY.1943-7900.0001831

Fuhg, J. N., and Bouklas, N. (2022). On physics-informed data-driven isotropic and anisotropic constitutive models through probabilistic machine learning and space-filling sampling. *Comput Methods Appl Mech Eng* 394:114915. doi: 10.48550/arXiv.2109.11028

Gaikwad, S, Asodekar, R, Gadia, S, and Attar, VZ. AGRI-QAS question-answering system for agriculture domain. In: *2015 international conference on advances in computing, communications and informatics, ICACCI 2015*. (2015).

García-Peñalvo, F. J. (2022). Developing robust state-of-the-art reports: Systematic Literature Reviews. *Educ. Knowledge Society.* 23, 307–308. doi: 10.14201/eks.28139

Garla, V. N., and Brandt, C. (2012). Ontology-guided feature engineering for clinical text classification. *J. Biomed. Inform.* 45, 992–998. doi: 10.1016/j.jbi.2012.04.010

Ghahari, A., Newlands, N. K., Lyubchich, V., and Gel, Y. R. (2019). Deep learning at the Interface of agricultural insurance risk and Spatio-temporal uncertainty in weather extremes. *N. Am. Actuar. J.* 23, 535–550. doi: 10.1080/10920277.2019.1633928

Gharibi, M., Zachariah, A., and Rao, P. (2020). FoodKG: a tool to enrich knowledge graphs using machine learning techniques. *Front Big Data.* 3:3. doi: 10.3389/fdata.2020.00012

Godara, S., and Toshniwal, D. (2020). Sequential pattern mining combined multi-criteria decision-making for farmers' queries characterization. *Comput. Electron. Agric.* 173:105448. doi: 10.1016/j.compag.2020.105448

Goldstein, A., Fink, L., Raphaeli, O., Hetzroni, A., and Ravid, G. (2019). Addressing the "tower of babel" of pesticide regulations: An ontology for supporting pest-control decisions. *J. Agric. Sci.* 157, 493–503. doi: 10.1017/S0021859619000820

Gomez-Perez, P, Phan, TN, and Kueng, J. Agricultural knowledge extraction from text sources using a distributed MapReduce cluster. In: *Proceedings - international workshop on database and expert systems applications, DEXA*. (2017).

Groumpos, PP, and Groumpos, VP. Modeling vineyards using fuzzy cognitive maps. In: *24th Mediterranean conference on control and automation, MED 2016*. (2016).

Gupta, H, and Das, Sheng VS. A roadmap to domain knowledge integration in machine learning. In: *Proceedings - 11th IEEE international conference on knowledge graph, ICKG 2020*. (2020).

Gutiérrez, CR. Advances in Knowledge Representation. (2012).

Haider, W., Rehman, A. U., Durrani, N. M., and Rehman, S. U. (2021). A generic approach for wheat disease classification and verification using expert opinion for knowledge-based decisions. *IEEE Access.* 9, 31104–31129. doi: 10.1109/ACCESS.2021.3058582

Hain, D. J., Wands, L., and Liehr, P. (2011). Approaches to resolve health challenges in a population of older adults undergoing hemodialysis. *Res. Gerontol. Nurs.* 4, 53–62. doi: 10.3928/19404921-20100330-01

Hajric, E. (2018). Knowledge management: system and practices a theoretical and practical guide for knowledge Management in Your Organization. *Eur. Manag. J.* 19.

Hatfield, J. L., Antle, J., Garrett, K. A., Izaurralde, R. C., Mader, T., Marshall, E., et al. (2020). Indicators of climate change in agricultural systems. *Clim. Chang.* 163, 1719–1732. doi: 10.1007/s10584-018-2222-2

Hills, M., and Fleiss, J. L. (1987). The design and analysis of clinical experiments. *J. R. Stat. Soc. Ser. A* 150:400. doi: 10.2307/2982050

Huang, Q., Wang, Y., Lyu, M., and Lin, W. (2020). Shape deviation generator-a convolution framework for learning and predicting 3-D printing shape accuracy. *IEEE Trans. Autom. Sci. Eng.* 17, 1–15. doi: 10.1109/TASE.2019.2959211

Ishizaka, A, and Nemery, P. (2013). Multi-criteria decision analysis: Methods and software. John Wiley & Sons.

Jakus, G., Milutinović, V., Omerović, S., and Tomažič, S. (2013). "Concepts BT - concepts, ontologies, and knowledge representation" in Concepts, ontologies, and knowledge representation. eds. G. Jakus, V. Milutinović, S. Omerović and S. Tomažič (New York, NY: Springer New York), 5–27.

Jearanaiwongkul, W., Anutariya, C., and Andres, F. (2019). A semantic-based framework for Rice Plant disease management: identification, early warning, and treatment recommendation using multiple observations. *N. Gener. Comput.* 37, 499–523. doi: 10.1007/s00354-019-00072-0

Jearanaiwongkul, W., Anutariya, C., Racharak, T., and Andres, F. (2021). An ontology-based expert system for rice disease identification and control recommendation. *App. Sci. (Switzerland).* 11, 841–842. doi: 10.3390/app112110450

Ji, X., and Lu, J. (2018). Forecasting riverine total nitrogen loads using wavelet analysis and support vector regression combination model in an agricultural watershed. *Environ. Sci. Pollut. Res.* 25, 26405–26422. doi: 10.1007/s11356-018-2698-3

Jurj, S. L., Grundt, D., Werner, T., Borchers, P., Rothemann, K., and Möhlmann, E. (2021). Increasing the safety of adaptive cruise control using physics-guided reinforcement learning. *Energies (Basel).* 14:7572. doi: 10.3390/en14227572

Kalita, H, Sarma, SK, and Choudhury, RD. Expert system for diagnosis of diseases of rice plants: prototype design and implementation. In: *International conference on automatic control and dynamic optimization techniques, ICACDOT 2016*. (2017).

Karpatne, A., Atluri, G., Faghmous, J. H., Steinbach, M., Banerjee, A., Ganguly, A., et al. (2017). Theory-guided data science: a new paradigm for scientific discovery from data. *IEEE Trans. Knowl. Data Eng.* 29, 2318–2331. doi: 10.1109/TKDE.2017.2720168

Karpatne, A., Watkins, W., Read, J., and Kumar, V. (2017). Physics-guided neural networks (PGNN): An application in lake temperature modeling. *arXiv*.

Kim, K. M., Hurley, P., and Duarte, J. P. (2022). Physics-informed machine learning-aided framework for prediction of minimum film boiling temperature. *Int. J. Heat Mass Transf.* 191:122839. doi: 10.1016/j.ijheatmasstransfer.2022.122839

Kitchenham, B. (2004). Procedures for performing systematic reviews. UK and National ICT Australia: Keele University, 33.

Kitchenham, B., Pearl Brereton, O., Budgen, D., Turner, M., Bailey, J., and Linkman, S. (2009). Systematic literature reviews in software engineering - a systematic literature review. *Inf. Softw. Technol.* 51, 7–15. doi: 10.1016/j.infsof.2008.09.009

Kohtz, S., Xu, Y., Zheng, Z., and Wang, P. (2022). Physics-informed machine learning model for battery state of health prognostics using partial charging segments. *Mech. Syst. Signal Process.* 172, 172:109002. doi: 10.1016/j.ymssp.2022.109002

Kulmanov, M., Smaili, F. Z., Gao, X., and Hoehndorf, R. (2021). Semantic similarity and machine learning with ontologies. *Brief. Bioinform.* 22, 1448–1449. doi: 10.1093/bib/bbaa199

Kung, H. Y., Yu, R. W., Chen, C. H., Tsai, C. W., and Lin, C. Y. (2021). Intelligent pig-raising knowledge question-answering system based on neural network schemes. *Agron. J.* 113, 906–922. doi: 10.1002/agj2.20622

Lin, Y., Jun, Z., Hongyan, M., Zhongwei, Z., and Zhanfang, F. (2018). A method of extracting the semi-structured data implication rules. *Procedia Computer Sci.* 131, 706–716. doi: 10.1016/j.procs.2018.04.315

Ling, J., Kurzawski, A., and Templeton, J. (2016). Reynolds averaged turbulence modelling using deep neural networks with embedded invariance. *J. Fluid Mech.* 807, 155–166. doi: 10.1017/jfm.2016.615

Lu, D., Konapala, G., Painter, S. L., Kao, S. C., and Gangrade, S. (2021). Streamflow simulation in data-scarce basins using bayesian and physics-informed machine learning models. *J. Hydrometeorol.* 22, 1421–1438. doi: 10.1175/JHM-D-20-0082.1

Lu, Y., Rajora, M., Zou, P., and Liang, S. Y. (2017). Physics-embedded machine learning: case study with electrochemical micro-machining. *Mach. Des.* 5, 1470–1471. doi: 10.3390/machines5010004

Lyubchich, V., Newlands, N. K., Ghahari, A., Mahdi, T., and Gel, Y. R. (2019). Insurance risk assessment in the face of climate change: integrating data science and statistics. *Wiley Interdis. Rev.: Computational Stat.* 11:e1462. doi: 10.1002/wics.1462

MacInnes, J., Santosa, S., and Wright, W. (2010). Visual classification: expert knowledge guides machine learning. *IEEE Comput. Graph. Appl.* 30, 8–14. doi: 10.1109/MCG.2010.18

Madaki, M. Y., Kaechele, H., and Bavorova, M. (2023). Agricultural insurance as a climate risk adaptation strategy in developing countries: a case of Nigeria. *Clim. Pol.* 23, 747–762. doi: 10.1080/14693062.2023.2220672

Malik, N., Hijam, D., and Sharan, A. (2021). Ontology based knowledge representation: case study from agriculture domain. *Int. J. Knowledge-Based and Intel. Engineer. Syst.* 25, 97–108. doi: 10.3233/KES-210055

Mangani, K. P., and Kousalya, R. (2019). Designing weather based crop insurance payout estimation based on agro-meteorological data using machine learning techniques. *Int. J. Recent Technol. Engineer.* 8, 2953–2960. doi: 10.35940/ijrte.C4806.098319

Mangasarian, O. L., and Wild, E. W. (2008). Nonlinear knowledge-based classification. *IEEE Trans. Neural Netw.* 19, 1826–1832. doi: 10.1109/TNN.2008.2005188

Maya Gopal, P. S., and Bhargavi, R. (2019). A novel approach for efficient crop yield prediction. *Comput. Electron. Agric.* 165:104968. doi: 10.1016/j.compag.2019.104968

Mazandu, G. K., Chimusa, E. R., and Mulder, N. J. (2017). Gene ontology semantic similarity tools: survey on features and challenges for biological knowledge discovery. *Brief. Bioinform.* 18:bbw067. doi: 10.1093/bib/bbw067

McMeekin, N., Wu, O., Germeni, E., and Briggs, A. (2020). How methodological frameworks are being developed: evidence from a scoping review. *BMC Med. Res. Methodol.* 20:173. doi: 10.1186/s12874-020-01061-4

Mehta, V., Bawa, S., and Singh, J. (2021). Stamantic clustering: combining statistical and semantic features for clustering of large text datasets. *Expert Syst. Appl.* 174:114710. doi: 10.1016/j.eswa.2021.114710

Meng, H., An, X., and Xing, J. (2022). A data-driven Bayesian network model integrating physical knowledge for prioritization of risk influencing factors. *Process. Saf. Environ. Prot.* 160, 434–449. doi: 10.1016/j.psep.2022.02.010

Mežnar, S., Bevec, M., Lavrač, N., and Škrlj, B. (2022). Ontology completion with graph-based machine learning: a comprehensive evaluation. *Mach Learn Knowl Extr.* 4, 1107–1123. doi: 10.3390/make4040056

Mudunuru, M. K., and Karra, S. (2021). Physics-informed machine learning models for predicting the progress of reactive-mixing. *Comput. Methods Appl. Mech. Eng.* 374:113560. doi: 10.1016/j.cma.2020.113560

Mummigatti, K. V. K., Chandramouli, S. M., and Ramachandra, D. H. (2023). Deep neural network system using ontology to recommend organic fertilizers for a sustainable agriculture. *Ingenierie des Systemes d'Information.* 28, 461–467. doi: 10.18280/isi.280222

Mungall, C. J., Bada, M., Berardini, T. Z., Deegan, J., Ireland, A., Harris, M. A., et al. (2011). Cross-product extensions of the gene ontology. *J. Biomed. Inform.* 44, 80–86. doi: 10.1016/j.jbi.2010.02.002

Muralidhar, N, Islam, MR, Marwah, M, Karpatne, A, and Ramakrishnan, N. Incorporating prior domain knowledge into Deep neural networks. In: *Proceedings - 2018 IEEE international conference on big data, big data 2018*. (2019).

Nismi Mol, E. A., and Santosh Kumar, M. B. (2023). Review on knowledge extraction from text and scope in agriculture domain. *Artif. Intell. Rev.* 56, 4403–4445. doi: 10.1007/s10462-022-10239-9

Pérez-Fuillerat, N., Solano-Ruiz, M. C., and Amezcua, M. (2019). Conocimiento tácito: características en la práctica enfermera. *Gac. Sanit.* 33, 191–196. doi: 10.1016/j.gaceta.2017.11.002

Porth, L., Tan, K. S., and Zhu, W. (2019). A relational data matching model for enhancing individual loss experience: An example from crop insurance. *N. Am. Actuar. J.* 23, 551–572. doi: 10.1080/10920277.2019.1634595

Porth, L., Zhu, W., and Tan, K. S. (2014). A credibility-based Erlang mixture model for pricing crop reinsurance. *Agricul. Finance Rev.* 74, 162–187. doi: 10.1108/AFR-04-2014-0006

Prasarnphanich, P., Janz, B. D., and Patel, J. (2016). Towards a better understanding of system analysts' tacit knowledge: a mixed method approach. *Inf. Technol. People* 29, 69–98. doi: 10.1108/ITP-06-2014-0123

Qian, E., Kramer, B., Peherstorfer, B., and Willcox, K. (2020). Lift & learn: physics-informed machine learning for large-scale nonlinear dynamical systems. *Physica D.* 406:132401. doi: 10.1016/j.physd.2020.132401

Ramamurthy, R, Bauckhage, C, Sifa, R, Schücker, J, and Wrobel, S. Leveraging domain knowledge for reinforcement learning using MMC architectures. In: Lecture notes in computer science (including subseries lecture notes in artificial intelligence and lecture notes in bioinformatics). (2019).

Ramasubramanian, J. A. (2012). Willingness to pay for index based crop insurance in India. USA: NEUDC 2012, Darmouth College.

Raymond, S. J., Cecchi, N. J., Alizadeh, H. V., Callan, A. A., Rice, E., Liu, Y., et al. (2022). Physics-informed machine learning improves detection of head impacts. *Ann. Biomed. Eng.* 50, 1534–1545. doi: 10.1007/s10439-022-02911-6

Read, J. S., Jia, X., Willard, J., Appling, A. P., Zwart, J. A., Oliver, S. K., et al. (2019). Process-guided Deep learning predictions of Lake water temperature. *Water Resour. Res.* 55, 9173–9190. doi: 10.1029/2019WR024922

Rhem, AJ. (2005). UML for developing knowledge management systems. Auerbach Publications.

Robinson, P. N., and Haendel, M. A. (2020). Ontologies, knowledge representation, and machine learning for translational research: recent contributions. *Yearb. Med. Inform.* 29, 159–162. doi: 10.1055/s-0040-1701991

Roscher, R., Bohn, B., Duarte, M. F., and Garcke, J. (2020). Explainable machine learning for scientific insights and discoveries. *IEEE Access.* 8, 42200–42216. doi: 10.1109/ACCESS.2020.2976199

Rousi, M., Sitokonstantinou, V., Meditskos, G., Papoutsis, I., Gialampoukidis, I., Koukos, A., et al. (2021). Semantically enriched crop type classification and linked earth observation data to support the common agricultural policy monitoring. *IEEE J Sel Top Appl Earth Obs Remote Sens.* 14, 529–552. doi: 10.1109/JSTARS.2020.3038152

Roznik, M., Brock Porth, C., Porth, L., Boyd, M., and Roznik, K. (2019). Improving agricultural microinsurance by applying universal kriging and generalised additive models for interpolation of mean daily temperature. *Geneva Papers on Risk and Insurance: Issues Prac.* 44, 446–480. doi: 10.1057/s41288-019-00127-9

Ruas, T, and Grosky, W. Semantic feature structure extraction from documents based on extended lexical chains. In: *GWC 2018 - 9th global WordNet conference*. (2018).

Saha, A., Singh, K. N., Ray, M., and Rathod, S. (2020). A hybrid spatio-temporal modelling: an application to space-time rainfall forecasting. *Theor. Appl. Climatol.* 142:1271. doi: 10.1007/s00704-020-03374-2

Sahoo, S. S., Kobow, K., Zhang, J., Buchhalter, J., Dayyani, M., Upadhyaya, D. P., et al. (2022). Ontology-based feature engineering in machine learning workflows for heterogeneous epilepsy patient records. *Sci. Rep.* 12:19430. doi: 10.1038/s41598-022-23101-3

Sansana, J., Joswiak, M. N., Castillo, I., Wang, Z., Rendall, R., Chiang, L. H., et al. (2021). Recent trends on hybrid modeling for industry 4.0. *Comput. Chem. Eng.* 151:107365. doi: 10.1016/j.compchemeng.2021.107365

Schröder, L., Dimitrov, N. K., Verelst, D. R., and Sørensen, J. A. (2022). Using transfer learning to build physics-informed machine learning models for improved wind farm monitoring. *Energies (Basel).* 15:558. doi: 10.3390/en15020558

Sepe, M., Graziano, A., Badora, M., di Stazio, A., Bellani, L., Compare, M., et al. (2021). A physics-informed machine learning framework for predictive maintenance applied to turbomachinery assets. *J. Global Power and Propulsion Society* 2021, 1–15. doi: 10.33737/jgpps/134845

Shirsath, P., Vyas, S., Aggarwal, P., and Rao, K. N. (2019). Designing weather index insurance of crops for the increased satisfaction of farmers, industry and the government. *Clim. Risk Manag.* 25:100189. doi: 10.1016/j.crm.2019.100189

Shrivastava, RR, and Deepak, G. BiCropRec: a bi-classifier approach for crop recommendation based on inclusion of semantic intelligence and topic modelling. In: Lecture notes in networks and systems. (2023).

Simumba, N, Okami, S, Kodaka, A, and Kohtake, N. Alternative scoring factors using non-financial data for credit decisions in agricultural microfinance. In: *4th IEEE international symposium on systems engineering, ISSE 2018 - proceedings*. (2018).

Smith, B., Ashburner, M., Rosse, C., Bard, J., Bug, W., Ceusters, W., et al. (2007). The OBO foundry: coordinated evolution of ontologies to support biomedical data integration. *Nat. Biotechnol.* 25, 1251–1255. doi: 10.1038/nbt1346

Soriano, M. A., Siegel, H. G., Johnson, N. P., Gutchess, K. M., Xiong, B., Li, Y., et al. (2021). Assessment of groundwater well vulnerability to contamination through physics-informed machine learning. *Environ. Res. Lett.* 16:084013. doi: 10.1088/1748-9326/ac10e0

Sottocornola, G., Baric, S., Stella, F., and Zanker, M. (2023). Development of a knowledge-based expert system for diagnosing post-harvest diseases of apple. *Agriculture (Switzerland).* 13, 1295–1296. doi: 10.3390/agriculture13010177

Spinner, T., Schlegel, U., Schäfer, H., and El-Assady, M. (2020). ExplAIner: a visual analytics framework for interactive and explainable machine learning. *IEEE Trans. Vis. Comput. Graph.* 26:1. doi: 10.1109/TVCG.2019.2934629

Staab, S., and Studer, R. (2009). Handbook on Ontologies. Berlin, Heidelberg: Springer.

Stucky, B. J., Guralnick, R., Deck, J., Denny, E. G., Bolmgren, K., and Walls, R. (2018). The plant phenology ontology: a new informatics resource for large-scale integration of plant phenology data. *Front. Plant Sci.* 9:9. doi: 10.3389/fpls.2018.00517

Sun, L., Gao, H., Pan, S., and Wang, J. X. (2020). Surrogate modeling for fluid flows based on physics-constrained deep learning without simulation data. *Comput. Methods Appl. Mech. Eng.* 361:112732. doi: 10.1016/j.cma.2019.112732

Sun, Z., Zhang, Q., Hu, W., Wang, C., Chen, M., Akrami, F., et al. (2020). A benchmarking study of embeddingbased entity alignment for knowledge graphs. *Proceed. VLDB Endowment* 13, 2326–2340. doi: 10.14778/3407790.3407828

Tartakovsky, A. M., Marrero, C. O., Perdikaris, P., Tartakovsky, G. D., and Barajas-Solano, D. (2020). Physics-informed Deep neural networks for learning parameters and constitutive relationships in subsurface flow problems. *Water Resour. Res.* 56:e2019WR026731. doi: 10.1029/2019WR026731

Tartarini, S., Vesely, F., Movedi, E., Radegonda, L., Pietrasanta, A., Recchi, G., et al. (2021). Biophysical models and meta-modelling to reduce the basis risk in index-based insurance: a case study on winter cereals in Italy. *Agric. For. Meteorol.* 300:108320. doi: 10.1016/j.agrformet.2021.108320

Thompson, M. (2017). Willingness to pay for agricultural risk insurance as a strategy to adapt climate change. *Accounting & FinanceUNU-MERIT*. 28.

Von Rueden, L., Mayer, S., Beckh, K., Georgiev, B., Giesselbach, S., Heese, R., et al. (2019). Informed machine learning - a taxonomy and survey of integrating knowledge into learning systems. *arXiv*. 3, 614–633.

Von Rueden, L., Mayer, S., Beckh, K., Georgiev, B., Giesselbach, S., Heese, R., et al. (2023). Informed machine learning - a taxonomy and survey of integrating prior knowledge into learning systems. *IEEE Trans. Knowl. Data Eng.* 35:1. doi: 10.1109/TKDE.2021.3079836

Wang, X. W., Du, M. Z., Wang, L., Li, M. X., Xu, Y. Y., Liu, X. Y., et al. (2018). Design of the continuous rainfall days index insurance of peanut in Henan Province. *Chinese J. Ecol.* 37, 3390–3395. doi: 10.48550/arXiv.1606.07987

Wang, J. X., Wu, J. L., and Xiao, H. (2017). Physics-informed machine learning approach for reconstructing Reynolds stress modeling discrepancies based on DNS data. *Phys Rev Fluids.* 2:034603. doi: 10.1103/PhysRevFluids.2.034603

Wei, T., Lu, Y., Chang, H., Zhou, Q., and Bao, X. (2015). A semantic approach for text clustering using WordNet and lexical chains. *Expert Syst. Appl.* 42, 2264–2275. doi: 10.1016/j.eswa.2014.10.023

Whyte, G., and Classen, S. (2012). Using storytelling to elicit tacit knowledge from SMEs. *J. Knowl. Manag.* 16, 950–962. doi: 10.1108/13673271211276218

Willard, J., Jia, X., Xu, S., Steinbach, M., and Kumar, V. (2020). Integrating Scientific Knowledge with Machine Learning for Engineering and Environmental Systems. *ACM Comp Syst.* 1, 1–35. doi: 10.48550/arXiv.2003.04919

Wu, J. L., Xiao, H., and Paterson, E. (2018). Physics-informed machine learning approach for augmenting turbulence models: a comprehensive framework. *Phys Rev Fluids.* 3, 1474–1475. doi: 10.1103/PhysRevFluids.3.074602

Xiaoxue, L., Xuesong, B., Longhe, W., Bingyuan, R., Shuhan, L., and Lin, L. (2019). Review and trend analysis of knowledge graphs for crop Pest and diseases, vol. *7*: IEEE Access, 62251–62264.

Xie, Y. (2011). Values and limitations of statistical models. *Res Soc Stratif Mobil.* 29, 343–349. doi: 10.1016/j.rssm.2011.04.001

Yanchinda, J. Effective ontologies based on the STEM learning concept of organic Rice knowledge using knowledge engineering. In: *International symposium on wireless personal multimedia communications, WPMC*. (2019).

Yingying, L, Xiaoyan, Z, Xiaodong, Z, Shibin, L, Na, Z, and Min, S. Knowledge expression and reasoning model for tomato disease diagnosis. In: 2017 *3rd international conference on information management, ICIM 2017*. (2017).

Yu, T., Canales-Rodríguez, E. J., Pizzolato, M., Piredda, G. F., Hilbert, T., Fischi-Gomez, E., et al. (2021). Model-informed machine learning for multi-component T2 relaxometry. *Med. Image Anal.* 69:101940. doi: 10.1016/j.media.2020.101940

Yu, T., Li, Z., and Wu, D. (2019). Predictive modeling of material removal rate in chemical mechanical planarization with physics-informed machine learning. *Wear* 426-427, 1430–1438. doi: 10.1016/j.wear.2019.02.012

Zabinski, J. (2021). "American National Standards Institute (ANSI)" in Encyclopedia of computer science and technology. *3rd* Edn. Eds. M. J. Bates and M. N. Maack.(CRC Press) p. 3.

Zammit, J., Gao, J., Evans, R., and Maropoulos, P. (2018). A knowledge capturing and sharing framework for improving the testing processes in global product development using storytelling and video sharing. *Proc. Inst. Mech. Eng. B J. Eng. Manuf.* 232, 2286–2296. doi: 10.1177/0954405417694062

Zhai, Z., Chen, X., Zhang, Y., and Zhou, R. (2021). Decision-making technology based on knowledge engineering and experiment on the intelligent water-fertilizer irrigation system. *J. Comput. Methods Sci. Engineer.* 21, 665–684. doi: 10.3233/JCM-215117

Zhang, J., Zhang, Z., and Tao, F. (2020). Rainfall-related weather indices for three Main crops in China. *Int. J. Disaster Risk Sci.* 11, 466–483. doi: 10.1007/s13753-020-00283-w

Zhao, X., Shirvan, K., Salko, R. K., and Guo, F. (2020). On the prediction of critical heat flux using a physics-informed machine learning-aided framework. *Appl. Therm. Eng.* 164:114540. doi: 10.1016/j.applthermaleng.2019.114540

Zhu, X., Zou, Z., Qiao, B., Fang, K., and Chen, Y. (2021). A named entity recognition model based on ensemble learning. *J. Comput. Methods Sci. Engineer.* 21, 475–486. doi: 10.3233/JCM-204543

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Designing multifunctional forest systems in Northern Patagonia, Argentina

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Multifunctional productive systems based on native species management, a new paradigm that counters colonial worldviews, offer sustainable sources of food and materials while preserving biodiversity. Despite extensive discussions in herbaceous and agricultural systems, applying this concept to native forests in Northern Patagonia remains unclear. Multifunctional system implementation can be approached from a fractal perspective, with evaluations at the stand level being essential for understanding ecological processes across scales. Here, we exemplify research and management for multiple native species, integrating results from 10 years of field experiments on the impacts of biomass harvesting intensity (HI) on nine Nature's Contributions to People (NCPs), including habitat creation, pollination, soil formation, hazard regulation, prevention of invasions, and provision of energy, food, materials, and options. Our findings reveal that some regulating NCPs peak with null HI, while certain material and regulating NCPs maximize at the highest HI. Low to intermediate HI (30–50%) show a more balanced provision of all NCPs. Our results suggest that some biomass extraction is necessary to enhance most NCPs, emphasizing the importance of balancing material provisioning and biodiversity conservation in management schemes. We propose future directions for designing multifunctional forest systems, advocating for low-density plantation of native tree species with high wood quality within the natural forest matrix. This approach may yield higher NCPs levels over time compared to the current cattle breeding and wood extraction system, with implications beyond Patagonia, considering historical associations of such practices with colonial worldviews globally.

KEYWORDS

biodiversity, bioenergy, biomass, colonial practices, ecosystem services, forest management, fruit plants, Nature's Contributions to People

1 Introduction

During European colonization, the Americas underwent a significant transformation as Europeans aimed to establish control over vast, unfamiliar lands (Veracini, 2010; Hixson, 2013). This process involved reshaping ecosystems to serve economic interests, introducing crops, livestock, and agricultural practices (Kaltmeier et al., 2016, 2019; Ficek, 2019; Markowitz, 2022). Enterprises from dominant countries sought cost reduction and operational advantages, often overlooking the role of biodiversity in production (Bousfield, 2019; Kaltmeier et al., 2019). The dominant species introduced were typically exotic and potentially invasive (Fajardo et al., 2022), with significant consequences for indigenous populations and existing ecosystems (Laterra et al., 2021). In these productive systems shaped by colonial worldviews, questions arise about implementing management alternatives for the benefit of both nature and people.

When designing new management schemes, it is crucial to consider not only the short-term production of commodities but also the broader spectrum of contributions that ecosystems offer to people. Nature's Contributions to People (NCPs) encompass a diverse range of benefits and detriments resulting from human interactions with the natural world (Hill et al., 2021; Kachler et al., 2023). These contributions can be categorized into three groups: material, non-material, and regulating NCPs. Material NCPs include tangible resources such as water, food, fibers, and energy. Non-material NCPs cover subjective aspects, such as cultural identity and aesthetic inspiration. Regulating NCPs refer to nature's role in shaping environmental conditions (Hill et al., 2021). These concepts are integral to multifunctional productive systems, where ecosystems interact with society to produce a wide range of NCPs (Bruley et al., 2021).

In many rural systems, the capacity to simultaneously provide numerous NCPs has declined due to conventional intensification and agricultural expansion shaped by colonial worldviews (Fagerholm et al., 2020). The prevailing trend toward intensification primarily focused on maximizing a single NCP, like food or material production, often comes at the expense of other vital services such as biodiversity conservation, clean water provisioning, and the safeguarding of local knowledge, cultural identity, and cherished places (Renting et al., 2009; Song et al., 2020). Recognizing and capitalizing on opportunities to enhance system multifunctionality, offers a means to navigate the complex interplay between trade-offs and synergies among NCPs (Benz et al., 2020). Multifunctional productive systems play a pivotal role in supporting climate regulation and furnishing essential NCPs, fundamental to good quality of life (Sardeshpande and Shackleton, 2019; Song et al., 2020; Westholm and Ostwald, 2020). Structural, biological and productive diversity in these systems grants a larger capacity to adapt to ever changing scenarios and is related to higher socio-ecological resilience (i.e., recovery from disturbances, such as natural phenomena or market fluctuations; Foley et al., 2005; Hölting et al., 2019).

Forests provide multiple NCPs, including regulating contributions, such as climate regulation through carbon storage (Lal, 2005; Griscom et al., 2017; Zhang et al., 2021) and habitat provision for a diversity of organisms (Lindenmayer, 2016). Material contributions, such as the extraction of wood and non-wood products like fruits and seeds (Guariguata et al., 2010), and non-material contributions, such as those related to psychological aspects (e.g., developing a sense of place; Gould et al., 2014), are also integral. However, forests usually cannot maximize all these NCPs simultaneously due to trade-offs associated with their multivariate nature (Bennett et al., 2009). As a consequence, each forest management decision has intrinsic synergies and trade-offs (Duncker et al., 2012; Wang and Fu, 2013; Syswerda and Robertson, 2014). For example, partial cutting or uneven aged management is unsuitable for high biomass production but, as structural complexity increases, thereby improving habitat quality, it can improve other services like biodiversity conservation and carbon sequestration (Sing et al., 2018). Understanding how different management options affect NCPs, with an emphasis on revealing trade-offs and synergistic effects, is an approach toward attaining sustainable management that balances and maintains multiple NCPs.

The enduring legacy of colonization, and more recent global processes related with increasing consumption and climate change, is evident in contemporary forests of Patagonia. The proliferation of livestock establishments, exotic conifer plantations, and various exotic plant species (Raffaele et al., 2014) are all testimony of that legacy. These forests also bear the imprint of enduring traditions of conservation practices and urban development. This amalgamation, often unintentional, has given rise to a multifaceted regional management scenario, encompassing the stewardship of national territories, privately owned lands, and sovereignty claims advanced by indigenous communities (Laterra et al., 2021; Peri et al., 2021). In the Northern Patagonian region of Argentina in particular, native forests have frequently been perceived as unproductive, leading to their conversion to other uses (Raffaele et al., 2014). Notably, the introduction of livestock and invasive tree species had detrimental consequences within the region's ecosystem (Raffaele et al., 2014). Through trampling, browsing, and other factors, livestock breeding has resulted in deleterious impacts (Mazzini et al., 2018; Ballari et al., 2020; Rodríguez and Soler, 2023). In addition, exotic tree plantations have induced alterations characterized by invasive behavior, competitive interactions, and increased susceptibility to wildfires (Franzese et al., 2022; Fernandez et al., 2023). However, Northern Patagonian forests also maintain a high level of pristine conservation compared to other forests worldwide. In this complex scenario, it becomes imperative to improve our understanding of the implementation of multifunctional productive systems, unraveling the intricate web of interactions within them. This study holds global significance as it addresses the enduring impact of colonial legacies and contemporary challenges, such as climate change and increasing consumption, on forest systems. By advocating for multifunctional management approaches and emphasizing the importance of preserving Nature's Contributions to People (NCPs), it offers valuable insights applicable beyond Argentina, informing sustainable practices for forest management and conservation worldwide.

2 Advancing native species management and research in Patagonia

Patagonia hosts considerable diversity in ecological regions and plant species, ranging from arid steppe areas dominated by herbaceous vegetation to temperate rainforests with abundant trees (Dezzotti et al., 2019; Secretaría de Gobierno de Ambiente y Desarrollo Sustentable de la Nación, 2019; Rosas et al., 2021). In particular, Patagonian forests have historically provided various goods and services, with biodiversity conservation and wood supply being prominent (Peri et al., 2021). Combining low to mid-intensity forest harvesting enhances productivity, ecosystem health, and biodiversity conservation (Gadow et al., 2006; Coulin et al., 2019; Carron et al., 2020; Chillo et al., 2020; Goldenberg et al., 2020a; Nacif et al., 2020). Climate-smart forestry, for example through canopy openings, protects trees, facilitates the provision of non-wood forest products, and enhances forest growth (Löf et al., 2019; Nacif et al., 2021).

Plantations with native trees provide a sustainable alternative to exotic plantations, enhancing the environmental and social value of forests (Cusack and Montagnini, 2004). For example, enriching native woodlands with locally adapted, native tree species of high economic value preserves ecosystems without complete replacement, offering a product appreciated by the market without relegating key ecological interactions (Álvarez-Garreton et al., 2019; Altamirano et al., 2020). Successful tree plantations require careful species and provenance selection, as well as site preparation, offering economic benefits through biomass extraction of the natural forest as a by-product (Goldenberg et al., 2020a; Nacif et al., 2023). *Nothofagus* and *Austrocedrus* trees are good examples of native trees with high timber quality and suitability for sustainable management (Speziale and Ezcurra, 2011; Donoso and Promis, 2015). Suitable harvesting intensities combined with native tree plantations, can provide an optimal balance between economic benefits and biodiversity conservation. We advocate for more empirical research to test these trends, contributing to long-term strategies.

In addition to native tree species, native fruit plants are of interest when designing forest enrichment schemes for multifunctional systems. Plants yielding fleshy, edible fruits have become a focal point of research in Patagonia, due to their nutraceutical potential. In the Patagonian region, 73 species of plants with edible fleshy fruits were identified, ~80% of which are native (Chamorro and Ladio, 2020). When assessing the cultural importance of these edible plants, it became evident that native species held greater significance than their exotic counterparts. The native species with the highest cultural importance index among the edible flora of the region was *Berberis microphylla* G. Forst ("calafate"). This shrub is native to South America and produces solitary yellow flowers resulting in dark blue, fleshy, edible fruits. The collection of its fruits, leaves, stems, and roots is a traditional practice in Patagonia among indigenous peoples. It is a frequent component of the understory and one of the non-wood forest products with the greatest economic potential of the Patagonian forests, offering high antioxidant and anthocyanin content, surpassing that of other native species (Ruiz et al., 2013) and widely marketed exotic fruits. Because of this attribute, *B. microphylla* has gained market interest for various products. Its production can be complemented with that of other native species, like native strawberry [*Fragaria chiloensis* (L.) Mill.] and native currants (*Ribes* spp.), Patagonian raspberries (*Rubus geoides* Sm.), and maqui [*Aristotelia chilensis* (Molina) Stuntz], with important nutritional and nutraceutical properties (Schmeda-Hirschmann et al., 2019).

3 Data supporting the paradigm shift

To exemplify the multivariate response of different scenarios of native forest management, we evaluated the response of 10 indicators of nine NCPs to biomass harvesting in a specific ecosystem at the plot level. Indicator data were obtained from various published or in-press studies based on the same experimental plots in *Nothofagus antarctica* (G.Forst.) Oerst. forests of Río Negro province, Argentina. The study site ("Conciencia") is private land dedicated to forest conservation and research, located near El Foyel (41° 38′ S, 71° 29′ W). It has an annual mean temperature of 7.0°C, a mean winter temperature of 2.5°C, and an annual rainfall of 1,100 mm (Goldenberg et al., 2020b). The canopy is dominated by *N. antarctica*, *Diostea juncea* (Gill. et Hook.) Miers., *Maytenus boaria* Molina, *Schinus patagonicus* (Phil.) I.M. Johnst. ex Cabrera, *Lomatia hirsuta* Diels ex J.F.Macbr., and *Embothrium coccineum* J.R.Forst. and G.Forst., with the presence of *Austrocedrus chilensis* Pic. Serm. et Bizzarri (Coulin et al., 2019; Goldenberg et al., 2020b).

The experiment was designed to evaluate the effect of biomass extraction at different percentages of harvesting intensity (HI) on several response variables. During 2013, four treatments were implemented by delineating six strips per plot (31.5 × 45.0 m) with varying widths. These widths determined the extent of tree and shrub removal at ground level, with the treatments comprising 0% (no plant cover removal), 30% (1.5 m wide), 50% (2.5 m wide), and 70% (3.5 m wide) removal (Nacif et al., 2023). Within each of the plots, we planted six native tree species, namely, *Austrocedrus chilensis*, *Nothofagus dombeyi*, *N. pumilio*, *N. antarctica*, *N. alpina*, and *N. obliqua* and monitored tree survival and growth for 9 years (Nacif et al., 2023).

We selected response variables based on two criteria: the estimated variable had to be a clear indicator of an NCP and have a statistically significant response to HI. When more than one variable was related to an NCP, the variable that best represented each NCP was chosen based on the authors' professional opinion (Table 1). For hazard regulation, however, we focused on fire prevention, and included two separate indicators because they had opposite responses and were equally strong indicators (see details in Goldenberg et al., 2020b). These were: live fuel moisture content (%, henceforth related to "hazard regulation 1") and fuel amount ($m^2.ha^{-1}$, henceforth related to "hazard regulation 2"). Exceptionally, food provision values were obtained from the same site but not from the same experimental design. Here, we focus on *B. microphylla*, though it should be interpreted as an illustrative example. *Berberis microphylla* fruit production was evaluated through a natural gradient of canopy openness (Appendix Figure 3, Fioroni et al., 2022), selecting and averaging data from natural

TABLE 1 Summary of the 10 selected indicators for nine different Nature's Contributions to People (NCPs) evaluated at the same study site in *Nothofagus antarctica* woodlands.

NCP indicator	NCP category	NCP group	References	Sampling years
Litter structural α-diversity (H')	Habitat creation and maintenance	Regulating	Fernández et al., 2022	2016–2018
Fuel amount ($m^2.ha^{-1}$)	Hazard regulation (2)	Regulating	Goldenberg et al., 2020b	2015–2017
Live fuel moisture content (%)	Hazard regulation (1)	Regulating	Goldenberg et al., 2020b	2015–2017
Exotic pinaceae seedlings (No)	Invasion prevention	Regulating	Dimarco et al., 2024	2013–2016
Natives bees and wasps (Ln $ind.ha^{-1}$)	Pollination	Regulating	Agüero et al., 2022	2014–2019
Aerial soil cover ($m^2.ha^{-1}$)	Soil protection	Regulating	Goldenberg et al., 2020b	2015–2017
Firewood ($m^3.ha^{-1}$)	Energy	Material	Goldenberg et al., 2018, 2020a	2018
Total fruits ($fruits.plant^{-1}$)	Provision of food	Material	Fioroni et al., 2022	2020–2021
Multispecific height (m)	Provision of materials	Material	Nacif et al., 2023	2013–2021
Plant diversity (H')	Maintenance of options	Non-material	Goldenberg et al., 2020b	2015–2017

The table includes the broad NCP group, citation, and sampling years. Both hazard regulation indicators included relate to fire protection.

levels of canopy opening near the range of the experimental design values. For each variable, data were averaged for each level of HI to represent the average short-term response to HI (i.e., around 5 years) irrespective of particular year climatic conditions. Each variable was rescaled relative to the maximum value and compiled in radar plots to represent the multifunctionality of each of the four treatments. The variables "exotic Pinaceae seedlings" and "fuel amount" were multiplied by −1 so that desirable conditions (invasion prevention and hazard regulation, respectively) were represented by high score values.

Harvesting intensity affected the different regulating, material, and non-material NCPs (Figure 1). At one end of the spectrum, 0% HI scored highest at four NCPs that relate only to regulating contributions (Figure 1: habitat, hazard regulation 1, invasion prevention, soil protection) and scored lowest at five NCPs (Figure 1: materials, food, energy, pollination, hazard regulation 2). At the other end, 70% HI scored highest at four NCPs (Figure 1: two regulation and two material NCPs; also Appendix Figure 3) but scored lowest at four NCPs (i.e., those that were maximized with 0% of harvesting intensity). One indicator of fire protection was maximized (live fuel moisture), and the other minimized (fuel amount) at 0% HI. The opposite occurred in the 70% HI scenario. We intentionally included both variables because it is difficult to predict which has a greater effect on fire reduction. Material NCP was only provided with some degree of harvesting (Appendix Figures 1–3), and thus low to intermediate HIs (30 or 50%) had a more balanced provision of all NCPs (Figure 1). In particular, low HI (30%) provided seven NCPs and scored highest at only one. Intermediate HI (50%) was the only management option that provided all nine NCPs while also maximizing two types of NCPs: material and non-material (Figure 1).

4 Designing multifunctional forest systems

Sustainable management of native forests at the stand level proves to be both feasible and effective for enhancing distinct NCPs. However, to promote enduring, larger-scale effects, it is crucial to shift the paradigm from colonial worldviews to multifunctionality also across the landscape (see Introduction). While we presented data at the plot level (Section 3), designing multifunctional forest systems at a larger scale needs identifying landscape elements, modeling, and optimizing their configuration based on climatic, geomorphological, biological, cultural, and socio-economic variables. This approach will promote multiple NCPs and a good quality of life. Some practices identified as part of the colonial vision, such as cattle rearing, native wood extraction, and prescribed fires, may not necessarily be completely removed (Figure 2). These activities can coexist in the landscape as long as they are managed to ensure continuous biodiversity conservation and landscape diversity. We suggest six possible target objectives that should be considered when designing and implementing multifunctional forest systems.

- **Restore native forests as the main target in the working landscape matrix:** Passively native forest recovery may be possible by restraining human activities to different extents (particularly removal of livestock), or by active interventions that may include plantation of native trees and understory species, systematic removal of exotic seedlings/saplings, etc. Areas to restore should be prioritized based on their biodiversity importance and their potential to provide NCPs. Restoration times will highly depend on the current degradation status, the celerity of its detection, and management response (Puettmann and Bauhaus, 2023), as well as on internal and external factors, such as the occurrence of extreme weather events.
- **Progressively reduce livestock and exotic animals abundance and improve their management:** Many authors agree on free-range grazing from exotic livestock being detrimental to many native forest functions, especially due to soil compaction and seedlings depletion (Ballari et al., 2020; Rodríguez and Soler, 2023), but results depend on the forest system and its productivity, the variables measured, and the grazing history (Mazzini et al., 2018). Confining

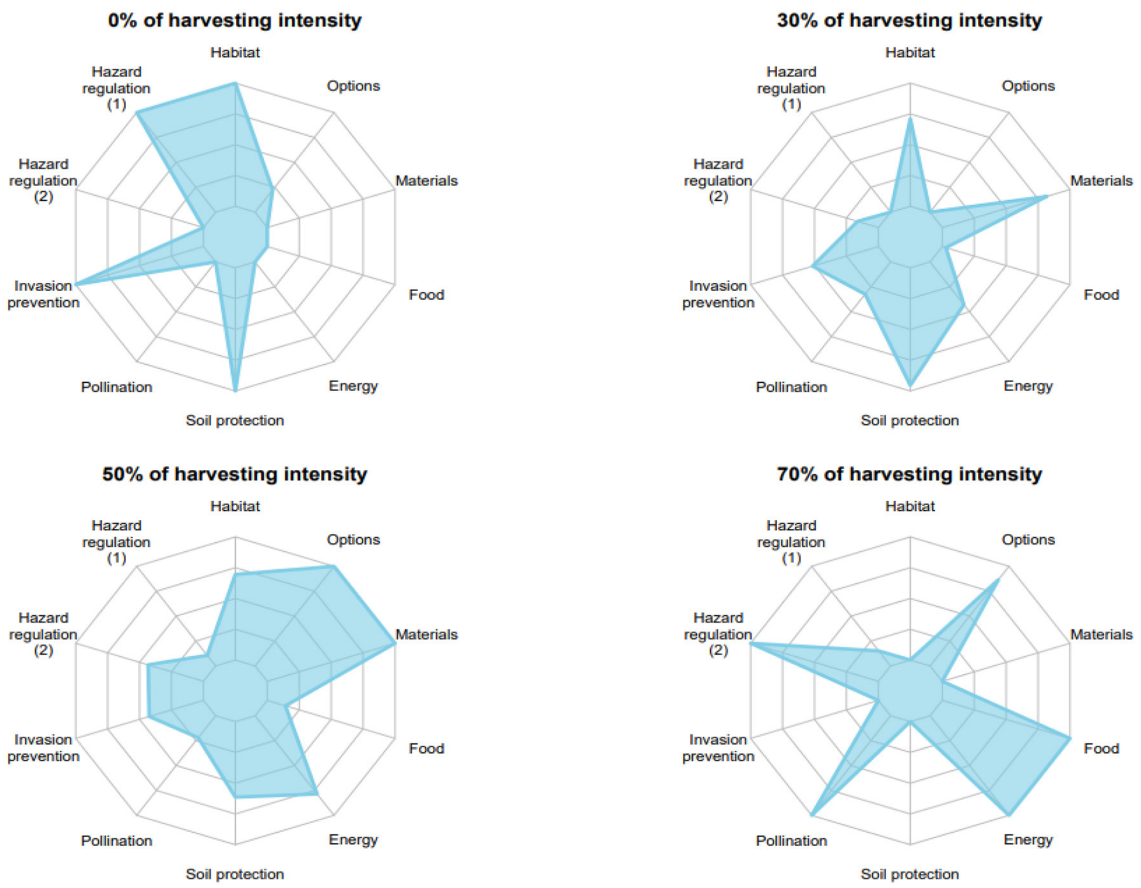

FIGURE 1
Low to intermediate harvesting intensities show a more balanced provision of all Nature's Contributions to People (NCPs). Effects of harvesting intensity (0, 30, 50, and 70%) on the 10 selected indicators (see Table 1) for nine NCPs evaluated at the same study site in *Nothofagus antarctica* woodlands. Data values were normalized by the maximum reported value for each variable. A full axis indicates that the NCP provision was maximized at the given harvesting intensity, while values closer to the center indicate that it was minimized. Hazard regulation NCP relates to fire protection and is calculated using two indicators: 1: live fuel moisture content, and 2: fuel amount.

livestock to designated areas, which may include forest patches under controlled silvopastoral practices, may offer a compromise solution. Frameworks such as the Forest Management with Integrated Livestock (Peri et al., 2022) can constitute useful tools, particularly if incorporated into legislation and financially supported and instrumented by governmental agencies.

- **Progressively reduce exotic plantations cover:** Multispecificity in planted forests has been shown to increase resilience and the provision of NCPs (Messier et al., 2022; this study). However, some exotic species, such as pinaceae, can become invasive with many detrimental effects. In this regard, attention will be needed to control exotic invasive saplings as early as possible (Núñez et al., 2017). These species may change the soil physico-chemical and hydrological properties, and thus, specific treatments may be needed to replace them with native species or a diversity of native and exotic species. Although distinct native species respond differently, it has been shown that through selective cuts, exotic species can shelter and benefit the establishment of newly planted native trees (e.g., Lesko and Jacobs, 2018).
- **Manage wood products and biomass extraction:** Wood is the main product extracted from forests, both for timber and fuel. While colonial worldviews have mainly focused on commercial criteria for forest harvesting, in recent decades, there has been increasing interest in applying management practices, such as retention forestry (Martínez Pastur et al., 2009; Gustafsson et al., 2012; Peri et al., 2021), and restoration thinning (Dwyer et al., 2010) due to their numerous co-benefits. Indeed, if these practices are planned appropriately, they can allow for trees, understory, and ground recovery while still admitting continuous harvesting in the long term.
- **Incorporate profitable alternatives:** While colonial practices are the current source of income for people living in and around native forests, replacing some of those activities, at least partially (e.g., reducing the animal load), may be possible if other commodities are added as forest values. Such alternatives can help dispel perceived trade-offs between conservation and profit. Examples of possible alternative include harvesting non-wood forest products (such as leaves, fibers, fruits, and fungi, collected for food, ornamental, aromatic, pharmaceutical, and medicinal purposes; Burgener

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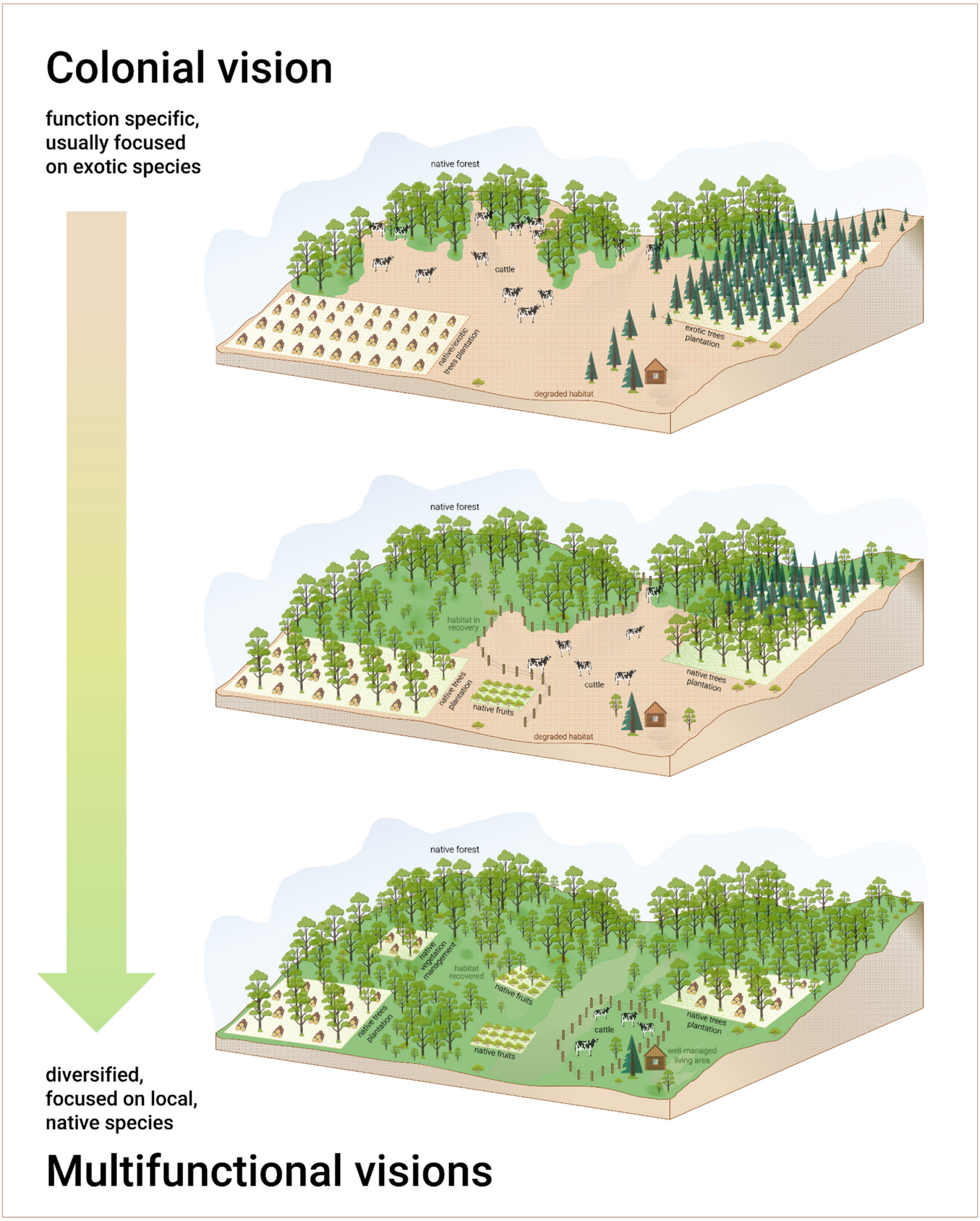

FIGURE 2
Transition from colonial to multifunctional native forest management. Currently, native forest lands present large degraded areas where land has been utilized for cattle rearing, unsustainable native wood extraction, and the introduction of exotic plantations. Although there are different degrees of degradation, colonial practices have been characterized by function-specific exploitation of habitats and resources, focusing on introduced species for livestock and timber production. The multifunctional views foster Nature's Contributions to People, aiming at dynamic diversification and maintenance of options for a better quality of life, acknowledging and attending to the needs associated with the multiplicity of realities on the territory. For example, it implies forest landscapes where people can live, develop more sustainable cattle-rearing practices, and manage native wood extraction, replacing existing plantations of exotic invasive species with native species. It also encompasses other forest products including cultivating/harvesting native fruits, ecotourism, biodiversity, and carbon offset credits.

and Walter, 2007) for local or regional trade, and different types of tourism (rural, scientific, and agrotourism). Mapping naturally occurring non-wood forest products patches on the landscape and incorporating new ones at selected locations can allow for more strategic management in terms of increasing biological and productive diversity. Biodiversity and carbon credits are also emerging as potentially profitable options. There are various global initiatives aiming at forest protection, restoration, and sustainable management (e.g., REDD+, COP26 Global Forest Finance Pledge; Garrett et al., 2022). For example, the global demand for carbon offset credits in the voluntary carbon market reached USD 6.7 billion in 2021 (Forest Trends' Ecosystem Marketplace, 2021). Although, in practice, skimming through administrative procedures has proven a daunting enterprise in many regions, and incentives do not yet reach many local communities, it is expected that these markets will grow greatly in the coming years. It is worth highlighting that intangible, non-marketable goods can also help transition to more sustainable visions (Hölting et al., 2019).

- **Design the size and arrangement of patches in the landscape:** Diversity at the landscape level with different patches emphasizing different NCPs is often most desirable (Grass et al., 2019). An example can include a combination of some patches with greater canopy opening for native fruit production next to others focused on wood production.

5 An iterative and participatory process

The previous objectives can be combined and are not independent of each other, requiring integral management and financial planning to ensure that at all steps of the transition, the activities align with conservation goals, as well as ensuring the livelihoods of the people that depend on the forest ecosystem over time. In this sense, the design and implementation of multifunctional forest systems should always be an iterative and participative process. In the anthromes context (Ellis and Ramankutty, 2008), relational values of people with the forests (e.g., cultural and identity attachment, local knowledge, ownership, and stewardship of lands and landscapes) are key to developing the transition (Fischer et al., 2017). These relational values are multidimensional and variable over time (Chillo et al., 2021), and therefore, approaches to multifunctionality should convene stakeholders from social, economic, governance, and cultural sectors involved at different scales (MEA, 2005) and be flexible enough to adapt to heterogeneous circumstances. Designing and implementing multifunctional landscapes in forested areas requires dealing with governance across sectors and scales and will need contemporizing legislation to accommodate a variety of current challenges, ranging from conservation laws to securing land tenure for local and indigenous peoples.

Given the natural and human-related complexity of forest landscapes, the transition may occur in several distinct phases (Figure 2). The vast assortment of stakeholders, needs, and interests around forest systems calls for flexibility and adaptability in the design and implementation of multifunctional forest systems. Therefore, monitoring, evaluating, and learning are crucial and should be done at different scales; a useful tool for this purpose is the establishment of permanent plots for long-term monitoring (Ceballos et al., 2022). At these steps, there are challenges related to selecting the relevant NCPs to measure and their indicators, assessing the use of and demand for those NCPs, and determining the right scale at which to evaluate multifunctionality (Hölting et al., 2019).

6 Limitations

While the study presents valuable insights into the potential benefits of implementing multifunctional landscape approaches for native forests in Northern Patagonia, several limitations and uncertainties must be acknowledged. Firstly, the study focuses on a specific ecosystem in a particular geographic region, potentially limiting the generalizability of its findings to other forests globally. Variations in climate, soil conditions, species composition, and human interventions may influence the outcomes of multifunctional management strategies differently across diverse ecosystems. Additionally, the study's reliance on data from a single experimental site over a relatively short period (i.e., around 5 years on average) raises questions about the long-term sustainability and robustness of the observed trends. Long-term monitoring and assessment of multifunctional systems initiatives are necessary to evaluate their effectiveness and resilience to changing environmental conditions and management practices. Finally, the proposed recommendations for designing multifunctional forest systems are based on a synthesis of existing literature and expert opinions, lacking empirical validation or stakeholder engagement to assess feasibility and acceptability in real-world contexts. Addressing these limitations and uncertainties through interdisciplinary research, long-term monitoring, stakeholder engagement, and adaptive management approaches will be essential for advancing the implementation of multifunctional forest systems worldwide.

7 Conclusions

Native forest in Northern Patagonia currently display the results of several decades to a little over a 100 years of colonial practices. Faced with ongoing climate and socio-environmental changes that pose serious threats to nature and people, establishing cornerstones for alternative visions is pivotal. We argue that such visions should be founded on landscape multifunctionality and the sustainable management of native species. We advocate for low-density cultivation of native forestry species within the natural forest matrix, while a minor fraction of the landscape can be subjected to greater canopy openness to enhance fruit production of native plants or livestock husbandry. Likewise, a minor fraction of the land can be used for the cultivation of fast-growing forest species. It is important to note that multifunctional landscape design complements but does not substitute the need to establish networks of protected areas, emphasizing distinct objectives (Kremen and Merenlender, 2018; Grass et al., 2019; Tscharntke et al., 2021).

As other authors have stated (e.g., Stanturf et al., 2019), there is no unique solution applicable to all cases of forest management and restoration. We argue for multiple, coexisting possible visions moving into the future, as opposed to a single, nostrum vision. These multifunctional visions foster nature's contributions to people, aiming at dynamic diversification and maintenance of options for a better quality of life, acknowledging and attending to the needs associated with the multiplicity of realities on the territory.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The manuscript presents research on animals that do not require ethical approval for their study.

Author contributions

LG: Writing – original draft, Writing – review & editing. PZ: Writing – original draft, Writing – review & editing. JA: Formal analysis, Writing – original draft, Writing – review & editing. MN: Formal analysis, Writing – original draft, Writing – review & editing. MGG: Formal analysis, Writing – original draft, Writing – review & editing. FF: Formal analysis, Writing – original draft, Writing – review & editing. MA: Writing – review & editing. AA: Writing – review & editing. RM: Writing – review & editing. MF: Writing – review & editing. NF: Writing – review & editing. MCG: Writing – review & editing. SN: Writing – review & editing. MAN: Writing – review & editing. FO: Writing – review & editing. MP: Writing – review & editing. JP: Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fsufs.2024.1357904/full#supplementary-material

References

Agüero, J. I., Coulin, C., Torretta, J. P., and Garibaldi, L. A. (2022). Invader complexes or generalist interactions? Seasonal effects of a disturbance gradient on plants and floral visitors. *For. Ecol. Manag.* 506:119963. doi: 10.1016/j.foreco.2021.119963

Altamirano, A., Miranda, A., Aplin, P., Carrasco, J., Catalán, G., Cayuela, L., et al. (2020). Natural forests loss and tree plantations: large-scale tree cover loss differentiation in a threatened biodiversity hotspot. *Environ. Res. Lett.* 15:abca64. doi: 10.1088/1748-9326/abca64

Álvarez-Garreton, C., Lara, A., Boisier, J., and Galleguillos, M. (2019). The impacts of native forests and forest plantations on water supply in Chile. *Forests* 10:60473. doi: 10.3390/f10060473

Ballari, S., Valenzuela, A., and Núñez, M. (2020). Interactions between wild boar and cattle in Patagonian temperate forest: cattle impacts are worse when alone than with wild boar. *Biol. Invasions* 22, 1681–1689. doi: 10.1007/s10530-020-02212-w

Bennett, E. M., Peterson, G. D., and Gordon, L. J. (2009). Understanding relationships among multiple ecosystem services. *Ecol. Lett.* 12, 1394–1404. doi: 10.1111/j.1461-0248.2009.01387.x

Benz, J. P., Chen, S., Dang, S., Dieter, M., Labelle, E. R., Liu, G., et al. (2020). Multifunctionality of forests: a white paper on challenges and opportunities in China and Germany. *Forests* 11:266. doi: 10.3390/f11030266

Bousfield, D. (2019). Settler colonialism in vegetal worlds: exploring progress and resilience at the margins of the Anthropocene. *Settl. Colon. Stud.* 10, 15–33. doi: 10.1080/2201473X.2019.1604297

Bruley, E., Locatelli, B., and Lavorel, S. (2021). Nature's contributions to people: coproducing quality of life from multifunctional landscapes. *Ecol. Soc.* 26:12. doi: 10.5751/ES-12031-260112

Burgener, M., and Walter, S. (2007). *Trade Measures—Tools to Promote the Sustainable Use of NWFP? An Assessment of Trade Related Instruments Influencing the International Trade in Non-wood Forest Products and Associated Management and Livelihood Strategies*. Rome: FAO.

Carron, A. I., Garibaldi, L. A., Marquez, S., and Fontenla, S. (2020). The soil fungal community of native woodland in Andean Patagonian forest: a case study considering experimental forest management and seasonal effects. *For. Ecol. Manag.* 461:117955. doi: 10.1016/j.foreco.2020.117955

Ceballos, S. J., Blundo, C., Malizia, A., Osinaga Acosta, O., Carilla, J., Hector Ricardo, G., et al. (2022). Red Argentina de Parcelas Permanentes de Bosques Nativos para promover colaboraciones científicas en estudios de largo plazo. *Ecol. Austral* 32, 361–367. doi: 10.25260/EA.22.32.2.0.1849

Chamorro, M. F., and Ladio, A. (2020). Native and exotic plants with edible fleshy fruits utilized in Patagonia and their role as sources of local functional foods. *BMC Complement. Med. Ther*. 20, 1–16. doi: 10.1186/s12906-020-02952-1

Chillo, V., Goldenberg, M., and Garibaldi, L.A. (2020). Diversity, functionality, and resilience under increasing harvesting intensities in woodlands of northern Patagonia. *For. Ecol. Manag*. 474:118349. doi: 10.1016/j.foreco.2020.118349

Chillo, V., Ladio, A. H., Salinas Sanhueza, J., Soler, R., Arpigiani, D. F., Rezzano, C. A., et al. (2021). "Silvopastoral systems in northern Argentine-Chilean Andean Patagonia: ecosystem services provision in a complex territory," in Ecosystem services in Patagonia: a multi-criteria approach for an integrated assessment, eds. P. L. Peri, G. Martínez Pastur, and L. Nahuelhual (Cham: Springer International Publishing), 115–137.

Coulin, C., Aizen, M. A., and Garibaldi, L. A. (2019). Contrasting responses of plants and pollinators to woodland disturbance. *Austral. Ecol*. 44, 1040–1051. doi: 10.1111/aec.12771

Cusack, D., and Montagnini, F. (2004). The role of native species plantations in recovery of understory woody diversity in degraded pasturelands of Costa Rica. *For. Ecol. Manag*. 188, 1–15. doi: 10.1016/S0378-1127(03)00302-5

Dezzotti, A., Mortoro, A., Medina, A., Sbrancia, R., and Beltrán, H. A. (2019). Plant richness and life form diversity along vegetation and forest use gradients in Northwestern Patagonia of Argentina. *CERNE* 25, 301–313. doi: 10.1590/01047760201925032645

Dimarco, R. D., Nacif, M. E., Garibaldi, L. A., and Nuñez, M. A. (2024). Higher establishment of nonnative trees with increased harvest intensity in strip cuttings. *New For*. 1–15. doi: 10.1007/s11056-024-10043-z

Donoso, P., and Promis, A. (2015). *Silvicultura en los bosques nativos: avances en la investigación en Chile, Argentina y Nueva Zelanda*. Valdivia: Marisa Cuneo Ediciones.

Duncker, P. S., Raulund-Rasmussen, K., Gundersen, P., Katzensteiner, K., De Jong, J., Ravn, H. P., et al. (2012). How forest management affects ecosystem services, including timber production and economic return: synergies and trade-offs. *Ecol. Soc*. 17:50. doi: 10.5751/ES-05066-170450

Dwyer, J. M., Fensham, R., and Buckley, Y. M. (2010). Restoration thinning accelerates structural development and carbon sequestration in an endangered Australian ecosystem. *J. Appl. Ecol*. 47, 681–691. doi: 10.1111/j.1365-2664.2010.01775.x

Ellis, E. C., and Ramankutty, N. (2008). Putting people in the map: anthropogenic biomes of the world. *Front. Ecol. Evol*. 6, 439–447. doi: 10.1890/070062

Fagerholm, N., Martín-López, B., Torralba, M., Otero-Rozas, E., Lechner, A., Bieling, C., et al. (2020). Perceived contributions of multifunctional landscapes to human well-being: evidence from 13 European sites. *People Nat*. 2, 217–234. doi: 10.1002/pan3.10067

Fajardo, A., Llancabure, J., and Moreno, P. (2022). Assessing forest degradation using multivariate and machine-learning methods in the Patagonian temperate rainforest. *Ecol. Appl*. 32:e2495. doi: 10.1002/eap.2495

Fernández, M. M., Casas, C., Bedano, J. C., Eissenstat, D. M., Kaye, M. W., García, I. M., et al. (2022). Mite density, not diversity, declines with biomass removal in Patagonian woodlands. *Appl. Soil Ecol*. 169:104242. doi: 10.1016/j.apsoil.2021.104242

Fernandez, R., Haubrock, P., Cuthbert, R., Heringer, G., Kourantidou, M., Hudgins, E., et al. (2023). Underexplored and growing economic costs of invasive alien trees. *Sci. Rep*. 13:8945. doi: 10.1038/s41598-023-35802-4

Ficek, R. (2019). Cattle, capital, colonization: tracking creatures of the Anthropocene in and out of human projects. *Curr. Anthropol*. 60, 260–271. doi: 10.1086/702788

Fioroni, F., Fernández, N., Fernández, M., and Garibaldi, L. (2022). La disponibilidad de luz limita la producción frutícola del calafate en un matorral mixto nativo (Río Negro, Argentina). *Ecol. Austral* 32, 984–989. doi: 10.25260/EA.22.32.3.0.1952

Fischer, J., Meacham, M., and Queiroz, C. (2017). A plea for multifunctional landscapes. *Front. Ecol. Environ*. 15:59. doi: 10.1002/fee.1464

Foley, J. A., Defries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., et al. (2005). Global consequences of land use. *Science* 309, 570–574. doi: 10.1126/science.1111772

Forest Trends' Ecosystem Marketplace (2021). *Market in Motion, State of the Voluntary Carbon Markets 2021, Instalment 1*. Washington DC: Forest Trends Association. Available at: https://www.forest-trends.org/publications/state-of-the-voluntary-carbon-markets-2021/ (accessed December 14, 2023).

Franzese, J., Raffaele, E., Chiuffo, M., and Blackhall, M. (2022). The legacy of pine introduction threatens the fuel traits of patagonian native forests. *Biol. Conserv*. 267:109472. doi: 10.1016/j.biocon.2022.109472

Gadow, K. V., Pukkala, T., and Tomé, M. (2006). Managing forest ecosystems. *Risk Anal*. 15:9. doi: 10.1007/978-94-015-9799-9

Garrett, L., Lévite, H., Besacier, C., Alekseeva, N., and Duchelle, M. (2022). *The Key Role of Forest and Landscape Restoration in Climate Action*. Rome: FAO.

Goldenberg, M. G., Gowda, J. H., Casas, C., and Garibaldi, L. A. (2018). Efecto de la tasa de descuento sobre la priorización de alternativas de manejo del matorral Norpatagónico argentino. *Bosque* 39, 217–226. doi: 10.4067/S0717-92002018000200217

Goldenberg, M. G., Oddi, F. J., Amoroso, M. M., and Garibaldi, L. A. (2020a). Effects of harvesting intensity and site conditions on biomass production of northern Patagonia shrublands. *Eur. J. For. Res*. 139, 881–891. doi: 10.1007/s10342-020-01292-6

Goldenberg, M. G., Oddi, F. J., Gowda, J. H., and Garibaldi, L. A. (2020b). Effects of firewood harvesting intensity on biodiversity and ecosystem services in shrublands of northern Patagonia. *For. Ecosyst*. 7, 1–14. doi: 10.1186/s40663-020-00255-y

Gould, R. K., Ardoin, N. M., Woodside, U., Satterfield, T., Hannahs, N., and Daily, G. C. (2014). The forest has a story: cultural ecosystem services in Kona, Hawai 'i. *Ecol. Soc*. 19:55. doi: 10.5751/ES-06893-190355

Grass, I., Loos, J., Baensch, S., Batáry, P., Librán-Embid, F., Ficiciyan, A., et al. (2019). Land-sharing/-sparing connectivity landscapes for ecosystem services and biodiversity conservation. *People Nat*. 1, 262–272. doi: 10.1002/pan3.21

Griscom, B. W., Adams, J., Ellis, P. W., Houghton, R. A., Lomax, G., Miteva, D. A., et al. (2017). Natural climate solutions. *Proc. Natl. Acad. Sci. U. S. A*. 114, 11645–11650. doi: 10.1073/pnas.1710465114

Guariguata, M. R., García-Fernández, C., Sheil, D., Nasi, R., Herrero-Jauregui, C., Cronkleton, P., et al. (2010). Compatibility of timber and non-timber forest product management in natural tropical forests: perspectives, challenges, and opportunities. *For. Ecol. Manag*. 259, 237–245. doi: 10.1016/j.foreco.2009.11.013

Gustafsson, L., Baker, S. C., Bauhus, J., Beese, W. J., Brodie, A., Kouki, J., et al. (2012). Retention forestry to maintain multifunctional forests: a world perspective. *BioScience* 62, 633–645. doi: 10.1525/bio.2012.62.7.6

Hill, R., Díaz, S., Pascual, U., Stenseke, M., Molnár, Z., and Van Velden, J. (2021). Nature's contributions to people: weaving plural perspectives. *One Earth* 4, 910–915. doi: 10.1016/j.oneear.2021.06.009

Hixson, W. (2013). *American Settler Colonialism, a History*. New York, NY: Palgrave Macmillan.

Hölting, L., Felipe-Lucia, M. R., and Cord, A. F. (2019). "Multifunctional landscapes," in *Encyclopedia of the World's Biomes*, eds. M. I. Goldstein, and D. A. DellaSala (Philadelphia: Elsevier), 128–134.

Kachler, J., Isaac, R., Martín-López, B., Bonn, A., and Felipe-Lucia, M. (2023). Co-production of nature's contributions to people: what evidence is out there? *People Nat*. 5, 1119–1134. doi: 10.1002/pan3.10493

Kaltmeier, O., Acker, A., and Tittor, A. (2016). Social production of nature. Between coloniality and capitalism. *FIAR* 9, 5–24.

Kaltmeier, O., Raab, J., Foley M. S., Nash, A., Rinke, S., and Rufer, M. (2019). *The Routledge Handbook to the History and Society of the Americas*. Abingdon: Routledge.

Kremen, C., and Merenlender, A. M. (2018). Landscapes that work for biodiversity and people. *Science* 362:eaau6020. doi: 10.1126/science.aau6020

Lal, R. (2005). Forest soils and carbon sequestration. *For. Ecol. Manag*. 220, 242–258. doi: 10.1016/j.foreco.2005.08.015

Laterra, P., Nahuelhual, L., Gluch, M., Peri, P., and Martínez-Pastur, G. (2021). "Imaginaries, transformations, and resistances in Patagonian territories from a socio-ecological perspective," in *Ecosystem Services in Patagonia. Natural and Social Sciences of Patagonia*, eds. P. L. Peri, G. Martínez Pastur, and L. Nahuelhual (Cham: Springer), 397–427.

Lesko, J., and Jacobs, D. F. (2018). Conversion of conifer plantations to native hardwoods: influences of overstory and fertilization on artificial regeneration. *New For*. 49, 829–849. doi: 10.1007/s11056-018-9683-z

Lindenmayer, D. (2016). Interactions between forest resource management and landscape structure. *Curr. Landsc. Ecol. Rep*. 1, 10–18. doi: 10.1007/s40823-016-0002-0

Löf, M., Madsen, P., Metslaid, M., Witzell, J., and Jacobs, D. (2019). Restoring forests: regeneration and ecosystem function for the future. *New For*. 50, 139–151. doi: 10.1007/s11056-019-09713-0

Markowitz, L. (2022). "Spanish settlers and Andean Food Systems," in *Going Native?* eds. R. Ranta, A. Colás, and D. Monterescu (Cham: Springer), 23–46.

Martínez Pastur, G. J., Lencinas, M. V., Cellini, J. M., Peri, P. L., and Soler Esteban, R. M. (2009). Timber management with variable retention in *Nothofagus pumilio* forests of Southern Patagonia. *For. Ecol. Manag*. 258, 436–443. doi: 10.1016/j.foreco.2009.01.048

Mazzini, F., Relva, M. A., and Malizia, L. R. (2018). Impacts of domestic cattle on forest and woody ecosystems in southern South America. *Plant Ecol*. 219, 913–925. doi: 10.1007/s11258-018-0846-y

MEA (2005). *Millennium Ecosystem Assessment*. Washington, DC: Island Press.

Messier, C., Bauhus, J., Sousa-Silva, R., Auge, H., Baeten, L., Barsoum, N., et al. (2022). For the sake of resilience and multifunctionality, let's diversify planted forests! *Conservation* 15:e12829. doi: 10.1111/conl.12829

Nacif, M.E., Kitzberger, T., and Garibaldi, L.A. (2020). Positive outcomes between herbivore diversity and tree survival: responses to management intensity in a Patagonian forest. *For. Ecol. Manag*. 458:117738. doi: 10.1016/j.foreco.2019.117738

Nacif, M.E., Quintero, C., and Garibaldi, L.A. (2021). Intermediate harvesting intensities enhance native tree performance of contrasting species while conserving herbivore diversity in a Patagonian woodland. *For. Ecol. Manag.* 483:118719. doi: 10.1016/j.foreco.2020.118719

Nacif, M. E., Goldenberg, M. G., Oddi, F. J., Pastorino, M. J., Aparicio, A. G., and Garibaldi, L. A. (2023). Plantación de especies forestales nativas en matorrales de Patagonia norte: respuesta a la apertura inicial de dosel en sitios contrastantes. *Bosque* 44, 219–239. doi: 10.4067/s0717-92002023000100219

Núñez, M. A., Chiuffo, M. C., Torres, A., Paul, T., Dimarco, R. D., Raal, P., et al. (2017). Ecology and management of invasive Pinaceae around the world: progress and challenges. *Biol. Invasions* 19, 3099–3120. doi: 10.1007/s10530-017-1483-4

Peri, P. L., Martínez-Pastur, G., and Schlichter, T. (2021). *Uso sostenible del bosque: Aportes desde la Silvicultura Argentina*. Ministro de Ambiente y Desarrollo Sostenible de la Nación. Buenos Aires.

Peri, P. L., Rosas, Y. M., López, D. R., Lencinas, M. V., Cavallero, L., and Martínez Pastur, G. (2022). Marco conceptual para definir estrategias de manejo en sistemas silvopastoriles para los bosques nativos. *Ecol. Austral* 32, 749–766. doi: 10.25260/EA.22.32.2.1.1872

Puettmann, K. J., and Bauhaus, J. (2023). Effects of lag time in forest restoration and management. *For. Ecosyst.* 10:100131. doi: 10.1016/j.fecs.2023.100131

Raffaele, E., De Torrres Curth, M., Morales, C., and Kitzberger, T. (2014). *Ecología e historia natural de la Patagonia Andina. Un cuarto de siglo de investigación en biogeografía, ecología y conservación*. Buenos Aires: Fundación de Historia Natural Félix de Azara.

Renting, H., Rossing, W. A. H.; Groot, J. C. J., Van der Ploeg, J. D., Laurent, C., Perraud, D., et al. (2009). Exploring multifunctional agriculture. A review of conceptual approaches and prospects for an integrative transitional framework. *J. Environ. Manag.* 90, 112–123. doi: 10.1016/j.jenvman.2008.11.014

Rodríguez, P., and Soler, R. (2023). Degraded forests display novel plant species assemblage: implications for sustainable livestock management in Southern Patagonia. *Agrofor. Syst.* 97, 907–916. doi: 10.1007/s10457-023-00835-1

Rosas, Y. M., Peri, P. L., Lencinas, M. V., Lasagno, R., and Martínez Pastur, G. (2021). Improving the knowledge of plant potential biodiversity-ecosystem services links using maps at the regional level in Southern Patagonia. *Ecol. Process* 10:53. doi: 10.1186/s13717-021-00326-0

Ruiz, A., Hermosín-Gutiérrez, I., Vergara, C., Von Baer, D., Zapata, M., Hitschfeld, A., et al. (2013). Anthocyanin profiles in south Patagonian wild berries by HPLC-DAD-ESI-MS/MS. *Food Res. Int.* 51, 706–713. doi: 10.1016/j.foodres.2013.01.043

Sardeshpande, M., and Shackleton, C. (2019). Wild edible fruits: a systematic review of an under-researched multifunctional NTFP (Non-Timber Forest Product). *Forests* 10:467. doi: 10.3390/f10060467

Schmeda-Hirschmann, G., Jiménez-Aspee, F., Theoduloz, C., and Ladio, A. (2019). Patagonian berries as native food and medicine. *J. Ethnopharmacol.* 241:111979. doi: 10.1016/j.jep.2019.111979

Secretaría de Gobierno de Ambiente y Desarrollo Sustentable de la Nación (2019). *Segundo Inventario Nacional de Bosques Nativos: informe bosque andino patagónico: primera revisión*. Buenos Aires: Secretaría de Gobierno de Ambiente y Desarrollo Sustentable de la Nación.

Sing, L., Metzger, M. J., Paterson, J. S., and Ray, D. (2018). A review of the effects of forest management intensity on ecosystem services for northern European temperate forests with a focus on the UK. *Int. J. For. Res.* 91, 151–164. doi: 10.1093/forestry/cpx042

Song, B., Robinson, G. M., and Bardsley, D. K. (2020). Measuring multifunctional agricultural landscapes. *Land* 9:260. doi: 10.3390/land9080260

Speziale, K., and Ezcurra, C. (2011). Patterns of alien plant invasions in northwestern Patagonia, Argentina. *J. Arid. Environ.* 75, 890–897. doi: 10.1016/j.jaridenv.2011.04.014

Stanturf, J. A., Kleine, M., Mansourian, S., Parrotta, J., Madsen, P., Kant, P., et al. (2019). Implementing forest landscape restoration under the Bonn Challenge: a systematic approach. *Ann. For. Sci.* 76:50. doi: 10.1007/s13595-019-0833-z

Syswerda, S. P., and Robertson, G. P. (2014). Ecosystem services along a management gradient in Michigan (USA) cropping systems. *Agric. Ecosyst. Environ.* 189, 28–35. doi: 10.1016/j.agee.2014.03.006

Tscharntke, T., Grass, I., Wanger, T. C., Westphal, C., and Batáry, P. (2021). Beyond organic farming—harnessing biodiversity-friendly landscapes. *Trends Ecol. Evol.* 36, 919–930. doi: 10.1016/j.tree.2021.06.010

Veracini, L. (2010). *Settler Colonialism: a Theoretical Overview*. London: Palgrave Macmillan.

Wang, S., and Fu, B. (2013). Trade-offs between forest ecosystem services. *For. Policy Econ.* 26, 145–146. doi: 10.1016/j.forpol.2012.07.014

Westholm, L., and Ostwald, M. (2020). Food production and gender relations in multifunctional landscapes: a literature review. *Agroforest Syst.* 94, 359–374. doi: 10.1007/s10457-019-00397-1

Zhang, J., Shen, X, Wang, Y., Jiang, M., and Lu, X. (2021). Effects of Forest changes on summer surface temperature in Changbai Mountain, China. *Forests*, 12:1551. doi: 10.3390/f12111551

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Sustainability-driven fertilizer recommender system for coffee crops using case-based reasoning approach

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Introduction: In recent years, the increased demand for food has prompted farmers to increase production to support economic expansion. However, the excessive use of mineral fertilizers poses a significant threat to the sustainability of food systems. In Colombia, coffee cultivation plays a fundamental role in the economy, thus creating a recognized demand to elevate its production while minimizing its environmental impact sustainably.

Methodology: The study follows the CRISP-DM methodology (Cross-Industry Standard Process for Data Mining) developing of a fertilizer recommender system (FRS) for coffee crops. This process includes business understanding, where the key factors influencing coffee production were identified; data understanding and preparation, where agroclimatic data and expert knowledge were collected and processed; modeling, which involved building a case-based reasoning (CBR) system to recommend fertilizer doses and frequencies, and evaluation, where expert feedback was gathered to assess the system's performance. The CBR system integrates soil, crop, and climate variables to provide tailored recommendations for nitrogen, phosphorus, and potassium applications.

Results: The results revealed that the FRS was deemed acceptable for application in the region, with expert evaluations rating the recommendations based on their experience and knowledge. Additionally, valuable feedback was provided to facilitate future enhancements to the system.

Discussion: Based on expert feedback and system performance, the proposed FRS meets the minimum requirements for deployment in real crops, serving as a valuable tool for small-scale farmers. Future work will expand the case base and refine recommender algorithms to improve accuracy and usability.

KEYWORDS

crop management, knowledge base farming, environmental sustainability, expert system, smart farming

1 Introduction

Agricultural production contributes to Colombia's economic growth and development, contributing 8.3% to the national gross domestic product (World Bank, 2022). However, agriculture substantially impacts the environment by producing food, fuel, and fibers to meet human needs (Boregowda et al., 2022). It is a leading cause of chemical and organic pollution to surface water and groundwater resources (Drechsel et al., 2023). It contributes to the release of greenhouse gasses (GHG) emissions (N2O), contributing to climate change (Rodríguez-Espinosa et al., 2023).

Colombia's four major export products are coffee, flowers, bananas, and sugar. Coffee, in particular, substantially impacts the country's economic growth, with 884,000 ha cultivated and 540,000 families relying on coffee production (Vélez-Vallejo, 2022; León-Burgos et al., 2022). The coffee industry is particularly affected by climate change, which threatens cultivable land and compels farmers to seek higher altitudes for optimal growing conditions for coffee crops (Bilen et al., 2023).

In this respect, coffee producers increasingly prioritize sustainability, which involves extra costs impacting farm profitability. Improving fertilizer application is one action that can contribute to sustainability and the reduction of climate change. Fertilizer misuse, particularly overapplication, significantly affects the economy and the environment (Martín Alonso et al., 2016). According to Lenka et al. (2016) and Sainju (2017), this is because crops typically utilize only 50–60% of the applied fertilizer, releasing a residual portion into the environment through natural processes such as leaching, denitrification, surface runoff, and soil erosion.

Analyzing agroclimatic and crop data is essential to provide accurate recommendations on coffee crop fertilizers and other agricultural inputs. This helps to improve crop efficiency and maintain environmental responsibility. Unfortunately, many small Colombian farmers do not have access to technological tools for data collection due to a lack of knowledge or education in using them (Chaves, 2016). Therefore, coffee farmers require better access to data about their crops, as there is a need for more data throughout the region (Sylvester et al., 2020). In this context, it is necessary to propose research studies that address fertilizer recommendations in scenarios with limited data, relying on scientific literature and expert knowledge (Howland et al., 2015).

This paper proposes a fertilizer recommender system (FRS) to address the environmental impact of fertilizer application in coffee crops in Colombia. The FRS was developed using a case-based reasoning (CBR) approach, a problem-solving methodology that uses past experiences or "cases" to inform new decisions. CBR operates by retrieving the most similar previous cases from a case base, reusing their solutions, revising them if necessary, and retaining the latest solutions for future use (Kolodner, 1992). In this context, the system integrates expert knowledge and agroclimatic data collected from local coffee growers and governmental institutions. The proposed FRS recommends the amount of nitrogen, phosphorus, and potassium fertilizer to be applied to a coffee crop, considering the balance between agricultural production and environmental preservation.

2 Related work

In recent years, the integration of intelligent systems in agriculture has gained significant momentum, with increasingly advanced systems combining expert knowledge with data. To explain these works, three main groups were classified based on the data sources used to generate recommendations or perform decision-support systems.

The first category includes works that collect data through sensors, leveraging real-time data from environmental sensors to monitor and adjust agricultural practices. The second category includes systems that rely on historical data, using past agricultural performance and weather trends to make predictions or provide recommendations. Finally, the third category encompasses systems that integrate expert knowledge, using the perspectives of farming professionals to guide decisions in crop management, fertilization, and pest control.

In the first category, the primary data collection method is sensor-based data gathering, where data from both the soil and the crop plant are collected. These data are subsequently analyzed and used to generate recommendations. For example, Kumar et al. (2019) developed a system that utilizes data from the soil, color sensors, and chemical processes to detect potential nutrient levels in the soil to provide fertilizer recommendations to small farmers in India in crops such as wheat, barley, corn, and sugar cane among others. Other studies, such as Wickramasinghe et al. (2019) and McFadden et al. (2018), employ machine learning algorithms like Support Vector Machines (SVM) and Bayesian models to analyze the data sensors to predict the necessary fertilizer quantities. In these works, the authors use previous information from the farmer that they combine with data from sensors that measure soil fertility to improve the estimation of agricultural production. The systems are developed and tested in small areas of crops where we can find corn, peanuts, beans, bananas, tomatoes, and sugarcane, among others. Among such works, Sujithra et al. (2019) developed a classification model where the input parameters consist of soil variables (where NPK, pH, temperature, and humidity stand out) collected by wireless sensors. The system experiments with J48, SVM, and k-means decision tree algorithms to select the most suitable classifier. The results indicated that the J48 algorithm better classified NPK availability in soil than the others, so it was chosen to make a more accurate classification. Subsequently, the data they collected in the field was taken as test data and compared with the trained data that had already entered the system to suggest fertilizers for cases with macronutrient deficiency in the soil.

The study by Qin et al. (2018) proposed a content-based RS for predicting the optimal nitrogen rate for corn crops in the USA. For this, they captured data from weather stations, sensors, and soil profile samples, then tested some ML algorithms such as Linear Regression (LR), Ridge Regression (RR), Most Minor Absolute Shrinkage and Selection Operator (LASSO), and Gradient Boosting Regression Trees (GBRT). To evaluate their results, they used R2, MAE, and RMSE. The ridge regression algorithm presented the best performance with 70% success in the evaluation. The research by Islam et al. (2020) enables the determination of nitrogen demand in plants using a dataset of 6,000 rice leaf images. These images were classified using a Convolutional Neural Network (CNN) and a decision tree to determine the necessary amount of nitrogen that farmers should apply.

The second category comprises studies about FRS based on the SVM algorithm to analyze historical data from governmental institutions. Suchithra and Pai (2018) created an FRS that generates fertilizer type and quantity recommendations in this category. Their system leverages historical records of soil and crop variables spanning multiple years. Another study in this category is Jiang et al. (2020), which used historical data such as applied nitrogen rates, crop yield, location, rainfall, temperature, pH, soil organic carbon, phosphorus, and potassium, from 31 experimental plots of 60 m^2 over 5 years located in the central corn producing region of northwest China, to construct a quadratic model. Puntel et al. (2019) employed some regression algorithms using data from 54 agroclimatic variables (like pH, organic matter, elevation, depth, previous crop yield, soil moisture, soil nitrate, precipitation, air temperature, and among others) which are obtained from historical databases and meteorological stations in the region, to recommend to farmers the optimal rate of nitrogen to apply. Vieira Fontoura et al. (2017) implemented an RS focused only on the nitrogen nutrient, designed for wheat and barley crops in Parana, Brazil. The proposed RS is based on content with data from 70 field experiments carried out between 2007 and 2012. These historical data correspond to Organic Matter (OM) values, pH, P, K, applied N rates, and the yield of the crops planted in that period. Thus, the system tries to obtain the maximum economic efficiency of N application rates in crops through data correlation analysis.

The second category also included studies where data could be more present, complete, or partially collected. These studies often rely on expert information to support their investigations. Ren and Lu (2012) and Zhang et al. (2011) proposed a DSS to recommend the most suitable fertilizers for specific crops, employing historical knowledge databases encompassing data from soil, crops, fertilization, and previous yields. Hossain and Siddique (2020) propose to address the problem of intensive input use in Bangladesh through the Soil Resources Development Institute's Online Fertilizer Recommender System (OFRS), which uses a national database to generate specific fertilizer recommendations. Cholissodin et al. (2016) developed a knowledge-based RS using experimental fertilizer data, employing algorithms such as Artificial Neural Networks (ANN) and Bayesian Improved Particle Swarm Optimization (BIPSO) to determine the required fertilizer dosage. Finally, a knowledge-based RS was also identified that utilizes fuzzy logic to recommend NPK fertilizer dosages, as presented by Sumaryanti et al. (2019).

The third category included studies that provide precise recommendations tailored to the specific needs of farmers and crops using expert knowledge represented as ontologies and agricultural data from sensors and image analysis. The drawback of works in this category, like Acuña (2019) and Chougule et al. (2019), which developed an RS that was fed with historical data and expert information from government databases, which was converted and stored in ontologies, subsequently the data were analyzed and studied with two machine learning algorithms: which were the grouping of k -means (k -means clustering) and random forest. The data that made up the knowledge base was a history of the last three years of the NPK content in the soil, the types of crops that grew in that soil, the climatic conditions, and what the production of those crops was like. Finally, with this history, the RS recommends to farmers based on the region, NPK content in the soil, and crop type, stating that the system's performance is highly accurate and that they expect it to achieve the goal of improving agricultural production in that country area.

While significant progress has been made in integrating sensor data, historical data, and expert knowledge for agricultural recommendations, several challenges remain. This study was conducted in the Cauca Department, a southwestern Colombia region, characterized by its diverse altitudes and predominantly Coffea arabica cultivation. The region's latitude influences the number of seasons, and coffee is often grown under shade trees rather than in full sun. One of the primary challenges in Cauca is the need for more data, as many farmers need access to advanced technological tools, which limits the integration of sensor and historical data. Future research should focus on developing scalable and adaptable systems that can leverage global data sets and expert knowledge to provide universally applicable recommendations, especially in technologically constrained regions.

3 Materials and methods

3.1 Phase 0: methods

Before developing the FRS, we conducted a Systematic Literature Review (SLR) following Kitchenham guidelines Kitchenham and Charters (2007) to identify relevant works in the field, as explained in the previous section. The objective was to identify agricultural smart systems and the most common and significant agroclimatic variables considered in these systems.

The SLR process began with an initial search in Scopus and Web of Science databases, focusing on Recommender Systems (RS), Prediction Systems, Decision Support Systems (DSS), and Expert Systems within the agricultural domain. After applying exclusion criteria to omit non-relevant works such as secondary sources, non-English publications, and non-agricultural studies, we identified 102 articles that met our inclusion criteria. These articles were further analyzed based on their geographic focus, with notable contributions from countries such as India (36), Indonesia (10), China (8), and the US (7).

In addition, we analyzed the agroclimatic variables used in these systems. The variables were categorized, and a bar chart (Figure 1) was generated to illustrate the frequency of these variables in the reviewed studies. The most frequently used variables were temperature (36 articles), pH levels (28 articles), disease incidence (26 articles), and soil moisture (16 articles). Other significant variables included soil NPK content (12 articles), crop yield (11 articles), crop type (11 articles), and pests (10 articles).

This analysis is visualized in Figure 2, which shows the distribution of the most used agroclimatic variables in smart systems within agriculture. The frequency of these variables highlights the diversity of factors that must be considered in agricultural decision-making systems, emphasizing the complexity of integrating environmental and crop-specific data.

The results of this SLR provided insights into the state of the art in smart agriculture systems and established a basis for the design of the system proposed in this work. This review also highlighted the importance of incorporating expert knowledge and agroclimatic data to improve the accuracy and relevance of recommendations.

Following this review, we adopted the CRISP-DM (Cross-Industry Standard Process for Data Mining) methodology to develop the FRS. The CRISP-DM phases that guided our development include business understanding, data understanding, modeling, and evaluation. The system was created in the Cauca Department, located in southwestern Colombia (with approximate

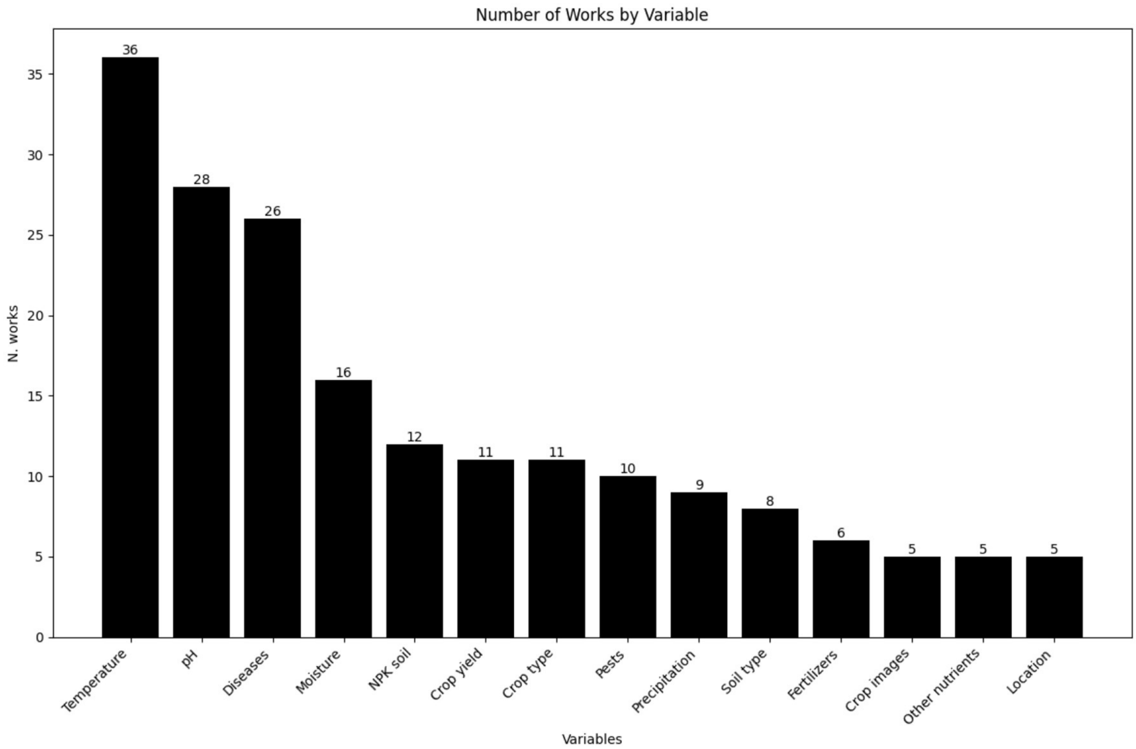

FIGURE 1
Input variables in the works.

coordinates of 2○30' N latitude and 76○30' W longitude). Cauca is characterized by a diverse range of altitudes (from 1,000 to 2,800 m above sea level), which influences its climate and, consequently, its agricultural practices. Coffee cultivation in Cauca primarily involves coffea arabica grown under shaded trees, although some coffee is grown in full sun. The region's latitude leads to distinct rainy and dry seasons, directly affecting fertilization practices. The phases of the CRISP-DM methodology applied in this work are detailed in the following sections.

3.2 Phase 1: study area

Initially, a business understanding was conducted to identify the critical factors in the development and growth of a crop. Like any other plant species, coffee cultivation requires essential elements for its development. Three of these elements, known as organic constituents, are freely available in the environment: carbon, hydrogen, and oxygen. According to Sadeghian (2008) they are obtained from water and the atmosphere, representing 95% of the plant's weight. The remaining 5% is found in the soil and is known as minerals, which are classified as macronutrients such as nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur, as well as micronutrients like iron, manganese, copper, boron, chlorine, molybdenum, and nickel.

It is essential to mention that macronutrients are required in larger quantities and are further categorized into primary macronutrients (N, P, and K) and secondary macronutrients (S, Ca, and Mg). However, while N, P, and K are applied annually as fertilizers, Ca and Mg are considered soil amendments. These amendments are typically used in a single dose, usually before planting, to correct soil pH. As Sadeghian Khalajabadi (2017) explained, although primary macronutrients are applied more frequently, the doses of Ca and Mg are calculated to have a long-term effect. Additionally, due to changes and climatic phenomena that occur over time, various natural processes can lead to the loss of these nutrients in the soil.

- Leaching: According to Sadeghian Khalajabadi et al. (2015), leaching is the displacement of nutrients and subtances below the crop's root zone toward water bodies due to excessive moisture in the soil.
- According to Valdivielso (2020), surface runoff is precipitation that flows over the soil surface under the influence of gravity without infiltrating into the soil.
- Erosion: the wearing away of the Earth's surface due to various natural events such as rainfall, sunlight, and natural disasters, as well as causes generated by human improper use of soil resources.
- Denitrification: due to the presence of a large number of microorganisms that use nitrite and nitrate instead of oxygen, the production of gaseous forms of nitrogen occurs, including nitrous oxide, which is one of the leading air pollutants, by Sadeghian Khalajabadi et al. (2015).

The fertilization process addresses the nutrient deficiency in the soil, which provides the necessary supplements for the

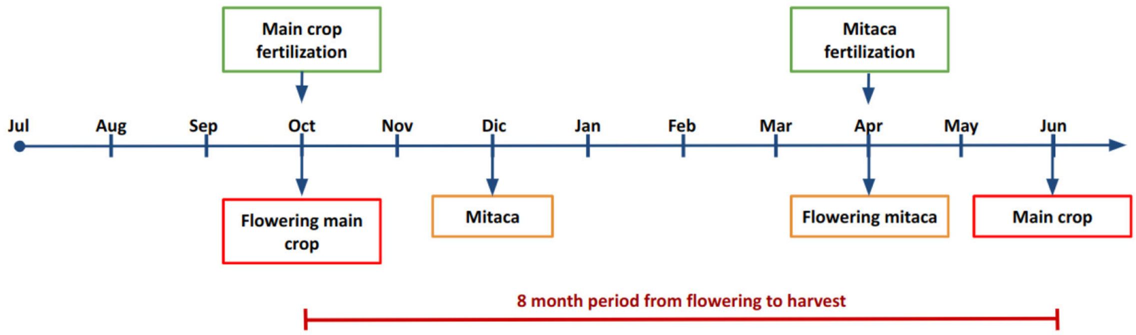

FIGURE 2
Schedule of coffee cultivation in Cauca (illustrated with experts).

plant to be productive and prevent nutrient losses. The fertilizer dose is typically calculated based on the crop's specific nutrient requirements, considering factors such as soil nutrient content, plant nutrient uptake, and expected yield. Soil testing is often used to determine the current levels of critical nutrients like N, P, and K, and recommendations are made to apply enough fertilizer to meet the plant's needs without over-fertilizing. Pozas (2008) states that one crucial factor to consider in this process is the stage of the crop. There are two stages in coffee crops: vegetative (juvenile) and production (adult). This study is centered around the production stage of coffee, which starts with the first crop harvest. It's worth noting that the timing and frequency of fertilizer application are just as important as the quantity applied. Hence, this initial phase also identifies the most appropriate periods for fertilizing a coffee crop during its production stage.

It is essential to recognize that crop fertilization needs to be timed correctly. It is crucial to determine the time from flowering to harvest for coffee crops. Figure 2 illustrates a coffee-growing period, known as a "coffee year." This figure shows two flowering periods and two harvest periods throughout the year.

In the Cauca department, the coffee year typically starts in July and ends in June of the following year. The flowering of the coffee crop usually occurs between September and November, with 8 months until the harvest or production of the crop. Thus, it is essential to fertilize the coffee during this period. However, coffee also has a second flowering, which results in a smaller harvest known locally as "Mitaca." The Mitaca typically represents 40–50% of the main harvest. Consequently, there are two periods of fertilization in coffee throughout the year to account for the main harvest and the Mitaca.

3.3 Phase 2: determination of variables

A study was conducted to collect data on the agroclimatic factors that affect crop fertilization or are considered significant from the domain perspective. The goal was to determine which variables would be addressed in the system. Afterward, these variables were gathered using a wireless sensor network, information provided by coffee farmers, and a service for extracting historical meteorological data from weather stations.

TABLE 1 Agroclimatic variables studied.

Variable type	Variable	Unit of measurement
Crop	Planting density	No. of plants per hectare (plan/ha)
Crop	Shade coverage	Percentage (%)
Crop	Flowering date	Date
Climate	Rainfall	millimeters of rain
Soil	N level	mg/kg
Soil	P level	mg/kg
Soil	K level	mg/kg
Soil	Moisture	Percentage (%)
Soil	pH	pH level

Determination of variables: This work involved collaborating with various agricultural experts affiliated with ECOTECMA SAS. Then, a knowledge base was constructed with their guidance. This involved a systematic compilation process encompassing reviewing reports, books, summaries, yearbooks, and bulletins sourced from CENICAFÉ. This knowledge base was constructed to determine the relevant soil, climate, and coffee crop variables deemed crucial for comprehensive study and analysis. Table 1 shows these variables.

Table 1 displays the fundamental variables for studying coffee crops. These variables are defined as follows:

- Planting density: This factor depends on the type of coffee planted by the coffee farmer, with the most common being Robusta coffee. A low planting density is considered when values are below 5,000 trees per hectare, and a medium or average density falls between 5,000 and 6,000 trees (approximate values for Robusta coffee), and a high density is considered when the number of trees per hectare exceeds 6,000, Arcila et al. (2007) noted.
- Shade coverage: This variable refers to the shade the coffee crop receives per hectare. It is measured in percentage, and low values are considered when below 30%, medium values range from 30 to 60%, and high values are above 60%. It is important to note that for proper development in coffee

crops, water availability, and sunlight exposure must be controlled to develop coffee crops properly. Effective shade management in the crop contributes to maintaining soil fertility, nutrient recycling, and erosion reduction (essential during dry seasons), supported by the findings of Farfán and Mestre (2004).
- The flowering date refers to the date when the crop flowers. Knowing this date is essential because, according to Sadeghian (2008), the fertilization process should be initiated on this day.
- Rainfall precipitation measures the accumulated rainfall in a specific region during a day. By studying these accumulations over a certain period, the state of the climatic season can be identified. Therefore, based on the collected expert information, it was determined to establish an analysis of historical meteorological data to classify the climatic season in a specific period (dry, normal, or rainy), as mentioned in Gast et al. (2013).
- Soil nitrogen: Nitrogen levels in coffee crops can range between 0 and 225 mg/kg. The appropriate nitrogen range is between 51 mg/kg for optimal crop development and 87 mg/kg. If nitrogen levels fall below 51 mg/kg, it leads to a nutritional deficiency. This shortage can adversely affect chlorophyll, essential for photosynthesis, thereby hindering the healthy growth of the plant. On the other hand, nitrogen levels exceeding 87 mg/kg suggest an overabundance or misuse of this nutrient. This represents waste from an economic standpoint for the farmer and carries the risk of causing environmental pollution. This information and the next were taken from Sadeghian Khalajabadi (2017).
- Soil phosphorus: The possible range of values in the soil is between 0 and 80 mg/kg, with suitable values for coffee crops falling between 10 and 20 mg/kg. If the values are below 10 mg/kg, the plant may exhibit uneven yellowing in older leaves, accompanied by reddish spots, and in severe cases, defoliation. If the value exceeds 20 mg/kg, it is considered a high soil phosphorus value, which can lead to the blocking of boron absorption in plants.
- Soil potassium: Its values range from 0 to 546 mg/kg. The appropriate values for coffee crops are between 78 and 156 mg/kg. A potassium value below 78 mg/kg reduces fruit size and leaf defoliation. If the potassium value exceeds 156 mg/kg, block in the absorption of micronutrients in plants.
- pH: Sadeghian Khalajabadi (2016) observes that it is measured on a scale of 0–14. The appropriate pH value for coffee crops should be between 5.5 and 6.5. If the soil pH is below 5, it is considered acidic soil, which affects the growth of plant roots and hinders the proper absorption of nutrients. It should be noted that acidic soils also block the absorption of potassium and nitrogen while promoting the absorption of manganese at levels that can be toxic to crops. If the pH is above 6.5, it leads to a blockage in the absorption of phosphorus, iron, zinc, and copper, resulting in a lower availability of these nutrients.

After the variables to be included in the development of this work were determined, the system architecture was designed, as shown in Figure 3. The collection and processing of data in the CBR system was done from three primary data sources that are integrated to generate the system recommendations:

IoT sensors in the field: A sensor network was deployed on a small farm in Piendamó, Cauca, to collect real-time critical soil data. The sensors include the 7-in-1 NPK, humidity, temperature, salinity, and electrical conductivity (EC). This sensor, with an NPK measurement range of 0 to 1,999 mg/kg and an accuracy of ±2%, was essential for measuring nutrient levels in the soil. The sensor sends its data to a collector via RS485, a communication protocol that ensures data transmission. The collector, in turn, transmits the data to a LORA gateway that uses RF communication at frequencies of 915–960 MHz with a range of up to 2 km. Finally, the data is sent via GPRS/GSM to a central server where it is stored and processed.

Features of the IoT devices used include:

- 7-in-1 NPK sensor: measures nitrogen, phosphorus, potassium, humidity, temperature and electrical conductivity with high accuracy and a resolution of 1 mg/kg for NPK.
- Collector: responsible for collecting and transmitting the data from the sensors, using the MODBUS-RTU protocol and LORA modulation with a range of up to 2 km.
- LORA gateway: device that connects the sensor data to the central server using network technologies such as GPRS and GSM.

Historical data comes from weather stations and public databases that record precipitation, temperature, and other agroclimatic conditions over time. This data is captured and sent to a processing server via HTTP. The server stores historical and real-time sensor data; for later use in the CBR. Besides automatically collecting data, the system feeds specialist information. This knowledge base contains rules and recommendations drawn from previous research and consultations with field professionals, which enriches the recommendations generated. Expert knowledge is integrated into the CBR system, which allows fertilization recommendations to be adjusted based on the specific farm context and soil conditions.

The system architecture therefore, combines three data sources: real-time sensors, historical databases, and expert knowledge. The central server processes all this data, allowing the CBR system to create new cases and make recommendations for crop fertilization. This integration of multiple sources of information makes it possible to improve the accuracy of recommendations and adapt them to the specific needs of each agricultural situation.

3.4 Phase 3: system construction

In this phase, an exploratory analysis of the variables determined in the previous section was conducted, identifying the numerical and categorical variables. Subsequently, the structure of each case in the CBR system was established, defining the data that constitute the problem and the solution for each case.

Case structure:

- Problem: This represents the part of the case that describes the situation that needs to be resolved or for which a solution needs to be found. It is represented by data or information that describes the need or problem. For the proposed CBR system, the problem consists of the variables determined in

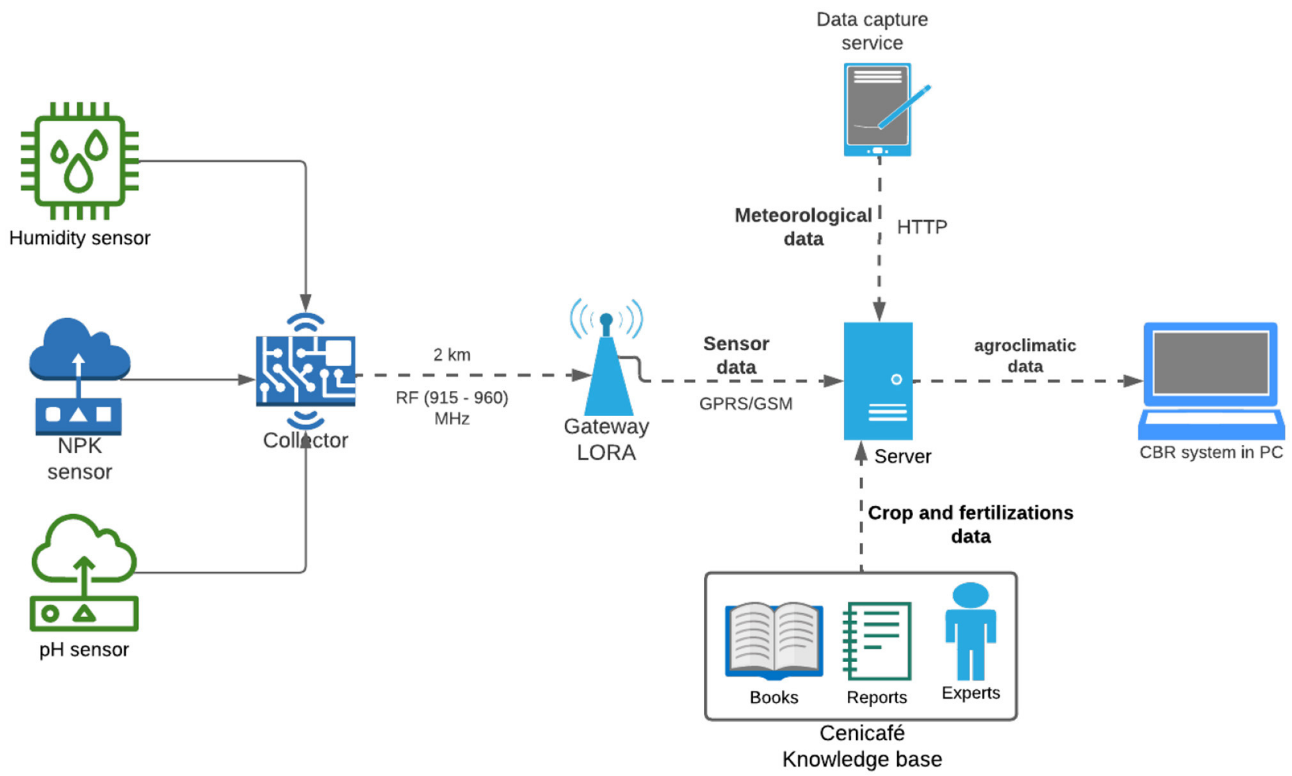

FIGURE 3
System architecture.

the previous section, except for the flowering date and rainfall precipitation, which are used to classify the climatic season that occurred 4 months before the flowering date.

- Solution: The solution was constructed using the system's output data, which corresponds to the fertilizer quantity rates that the system will recommend to the coffee farmer based on the data comprising the case problem. Three recommend fertilizer rates are provided due to the three most essential macronutrients identified in the first phase of CRISP-DM (N, P, and K).

3.4.1 Classification of climatic season

It is necessary to organize the climate seasons from 2006 to the established date to classify the climatic season based on the date of the last crop flowering. These seasons were identified based on historical records of dry or rainy periods each year obtained from the National Weather Service (2023). Using the classification provided by the NWS, eight years were identified as usual, five years as rainy, and three years as dry from 2006 to 2021.

With these historical classifications, historical data was analyzed to define a new classification of the climatic season for the year in which the last flowering date in the crop occurred. The mentioned classification was based on information suggested by experts. It involved obtaining the accumulated precipitation (PP) for the last 4 months before the flowering date and the historical accumulated PP for those same months in the years classified as standard within the 2006–2021 period. The obtained values are compared, and the season is categorized based on the comparison results. Suppose the accumulated PP in the year of the flowering date exceeds the historical average PP by more than 35%. In that case, the climatic season at that flowering date is classified as rainy. Conversely, the season is dry if the comparison shows that the accumulated PP is lower by 25% than the historical average. The season is classified as usual if these conditions still need to be met.

Therefore, by classifying a climatic season at the beginning of the fertilization period in the crop, the system can define the frequency of fertilizer application it recommends. According to expert information, applying fertilizer three times per period (at 2, 4, and 6 months after the flowering date) is appropriate if the season is classified as usual or rainy. On the other hand, if the season is classified as dry, applying fertilizer twice per period (at 3 and 6 months after the flowering date) is recommended.

3.4.2 Case base

The case base is the core of any CBR system, as it directly depends on the existence of a case base to perform all the steps in a CBR cycle, as Sànchez-Marrè (2001) mentioned. A case can be constructed by human experts or past experiences of the system. Cases can be represented in various ways, such as rules, logical formulas, frames, and database records (Shang, 2005). In this work, the case base was constructed, considering the knowledge base explained in the data collection process and determining variables for the system. Subsequently, experts validated this case base.

Different possible combinations of problem data were considered, and the most suitable solutions were determined based on expert knowledge. In each case, the variables of climatic season, humidity, pH, and NPK in the soil represent the problem of a case, and the fertilizer rate data represent the solution. For example, in a case where there is a rainy season, normal pH, low NPK, and high humidity, it may indicate unfavorable soil conditions for the crop, which would require a high NPK fertilizer rate. In this way, 300 problems are constructed, representing different situations that can occur in a coffee crop, and expert solutions are assigned to each of these problems, resulting in a case base of 300 cases.

3.5 Phase 4: modeling

In this phase, the model of the developed CBR system was implemented using Python. The CBR system follows the classic retrieval, reuse, revision, and retention steps described by Kolodner (1992), also known as the 4 R's of CBR. The first two steps in our implementation–retrieving the most similar cases and determining a new solution—were the focus. The data manipulation and case creation were done using Python libraries such as Pandas and Numpy, which facilitated the processing of historical climatic data and expert knowledge. These tools were used to build the case base for the system. The code was developed and tested in Python Notebooks, using the Google Colab platform to effectively run and visualize the results. This environment allowed for interactive data analysis and collab development, making refining the CBR model based on the input data easier.

- Retrieval: Given a new problem, the CBR system uses an algorithm to retrieve the cases that are most similar to it. Miller (2019) used the K-Nearest Neighbors (KNN) algorithm, which can be used for classification or regression tasks. This algorithm uses a factor k, which indicates the number of nearest neighbors (similar cases) to consider making a prediction.

  A comparison was made between each case data point using a similarity measure to find the most similar cases (nearest neighbors) given a new input. According to Gabel (2010), the choice of similarity measures in a CBR system depend on the composition of the problem variables. The Hamming distance or the Simple Matching Coefficient (SMC) is commonly used if the values are discrete. The cosine similarity measure is used if the data is symbolic or character strings. Similarly, the Manhattan, Euclidean, and Mahalanobis distances are used for real-valued numeric data. In this work, the Euclidean distance was chosen due to the numerical nature of the problem data and the advantage of feature weighting that this similarity measure possesses.

  Next, by calculating the distance between each data point of the two cases, similarities are obtained for each problem variable. It means that two problems can be similar from the perspective of a particular variable but entirely different when viewed from another variable. Therefore, assigning a weight to each variable was considered to strengthen the similarity in some variables rather than others. It is done based on the impact variables have on the crop, as not all variables affect it in the same proportion. For example, two problems that only differ in the shade of the crop cannot have the same similarity as two problems that only differ in the climatic season. In other words, the season has a more significant impact in considering those two problems differently. In summary of this step in CBR, a new entry is entered into the system, and the k most similar cases are obtained based on the Euclidean distance calculated between the incoming problem and each case stored in the case base.
- Reuse: With the identification of the k most similar cases, the solutions of those cases were reviewed to determine or adapt a new solution for the new problem. In CBR, Gabel (2010) observes different methods to find a new solution based on rules, conditions, formulas, expert guidance, and constraints. Additionally, one of the methods to determine a new solution is the regression technique, which was used to predict the fertilizer rates for the three studied macronutrients. Therefore, the average fertilizer rates from the most similar cases found were used to determine the fertilizer rates for the new problem.
- Recommendations: As explained earlier, the first three variables of a case's solution indicate the rates (low, medium, high, or very high) of NPK fertilizer to apply based on the general soil condition. After obtaining the predictions, these rates are converted into fertilizer amounts expressed in kilograms per hectare (kg/ha) per year. The recommended fertilizer rates were obtained through consultations with experts and studies from Cenicafé according to Sadeghian (2008) and FNC (2013). These studies determined the maximum amounts of N, P, and K fertilizer required for a coffee crop in Colombia, based on a case with high density and low shade.

  This study determined the fertilizer quantities for various soil conditions that can occur in a case. Additionally, these fertilizer quantities are scaled according to the crop planting density. Recommending a medium rate, for example, in a density of 3,000 plants per hectare, is different from making the same recommendation in a density of 7,000 plants per hectare. Therefore, it is essential to define three high rates for low, medium, and high planting densities and three medium rates for low, medium, and high densities in a periodical way. Table 2 presents the determined quantities for each studied nutrient, which domain experts validated.

3.6 Phase 5: evaluation

For this phase, the evaluation of the RS depends directly on the perspective of the application domain, in this case, agriculture; therefore, it is imperative to validate the findings in consultation with experts in the domain. This validation process would help alleviate the uncertainty of the developed model for future applications. Six case studies (randomly chosen from the case base) were addressed, covering information related to crops, soils, and climatic conditions. Table 3 shows the information for each case and the respective recommendation provided by the system, considering the units of measurement of each variable.

TABLE 2 Amount of fertilizer to recommend according to the crop's soil condition and planting density.

Nutrient	Fertilizer rate	Fertilizer quantity (kg/ha per year)		
		High density	Medium density	Low density
Nitrogen	Low	150	180	210
	Medium	180	210	240
	High	210	240	270
	Very high	240	270	300
Phosphorus	Low	30	36	42
	Medium	36	42	48
	High	42	48	54
	Very high	48	54	60
Potassium	Low	135	165	195
	Medium	165	195	225
	High	195	225	255
	Very high	225	255	295

These six cases were obtained from data collected by sensors on several farms in the Department of Cauca and information shared by Ecotecma experts in their investigations. In developing our RS, we have reached a level of technological maturity 3, indicating that our project has passed the theoretical phase and created a functional prototype, according to National Aeronautics and Space Administration (2017). This prototype has been designed to demonstrate the viability of the underlying RS concept; using the data and scenarios provided in the case above. While this prototype is functional, it is essential to note that it is designed for proof of concept and initial experimentation, rather than for large-scale implementation or commercial use. Future work will focus on advancing this prototype to higher TRL levels and improving the CBR KB, aiming to create a scalable recommender system that can be effectively adapted to various agricultural conditions and requirements.

The system evaluation involved the collaboration of six domain experts whose credentials and specific areas of experience provide significant validity to their assessments. These include:

- Expert 1: A Biologist with a Ph.D. in Environmental Sciences and postdoctoral experience in soil management in coffee agroecosystems. Over 7 years of experience in science, technology, and innovation in Colombia's agricultural sector and natural resource conservation.
- Expert 2: Agricultural Engineer, Master in Agroecology, PhD in Environment and Society, professor at the University of Cauca, and coordinator of the Agroecology and Territory component of the Center for Innovation and Social Appropriation of Coffee Growing.
- Expert 3: Agricultural Engineer. Agronomist at a coffee development company in the region.
- Expert 4: Agronomist Engineer. Agronomic Advisor and Researcher for the Cauca Soils Project at the Government of Cauca.
- Expert 5: Environmental engineer. Coordinator in environmental management activities in Cauca. Doctoral student in Telematics Engineering in the research field of agriculture.
- Expert 6: Business administrator and farmer.

The RS was evaluated using a structured survey. The process consisted of open recommendations for the first three cases and multiple-choice evaluations for the final three cases.

In the first part of the survey, experts were provided with information on three cases detailing crop, soil, and climate conditions. Based on their expert knowledge, they were asked to recommend the amounts of N, P, and K fertilizers to be applied per hectare per year. The system's recommendations were compared with these open responses, and subsequently, for the following three cases, the experts rated the system's suggestions using a modified Likert Scale (LS) (1 = Inadequate, 2 = Unsatisfactory, 3 = Acceptable, 4 = Effective, and 5 = Optimal).

Table 4 shows the recommendations given by the experts for the first three cases. As well as the recommendations generated by the RS. Likewise, Table 5 shows the expert's ratings for the following three cases, where each one made a general rating for the three recommendations (N, P and K) generated by the RS, based on the given options.

To analyze the similarity between the CBR system's recommendations and those provided by the experts, the Pearson correlation coefficient (PCC) was calculated for each case and nutrient. This coefficient measures the strength of the linear relationship between the two variables, in this case, the fertilization recommendations by the experts and those generated by the system. The coefficient results are shown at the end of Table 4, where the variability between the values is observed.

N shows a moderate correlation in the three cases, with values ranging between 0.578 and 0.665. A high correlation was observed for P in Case 1 (0.894). Still, in Case 2 the correlation was negative (−0.178), indicating significant discrepancies between the system's recommendations and those of the experts in that context. Finally, very high correlations were found for K, with values close to 1 in all three cases, suggesting a solid alignment.

To analyze the consistency and reliability of the expert's assessments, we calculated the Intraclass Correlation Coefficient (ICCa) using Python and the Pingouin library. The ICCa assesses agreement by analyzing the variance between the rater's ratings relative to the total variance. An ICCa value close to 1 indicates high consistency or agreement between raters, while a value close to 0 or negative reflects a lack of significant agreement. This metric is beneficial when assessing the reliability of assessments provided by different people using a similar scale.

For the first three cases, three coefficients were calculated based on the three recommendations given by each expert for each case. The results, divided by nutrient (N, P, and K), are presented below:

- ICCa for N: The ICCa for the expert's N recommendations was 0.266, indicating low agreement between experts. This

TABLE 3 System recommendations based on case information.

Variable	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Planting density (No. of plants per ha)	5,500	4,500	5,700	5,800	6,700	7,800
Shade coverage (%)	30	30	38	20	50	30
Climatic season	Rainy	Dry	Rainy	Rainy	Normal	Dry
Moisture soil (%)	50	30	75	60	35	15
N level soil (mg/kg)	40	60	45	60	95	55
P level soil (mg/kg)	12	6	8	42	80	60
K level soil (mg/kg)	196	100	125	216	160	93
pH soil	5.2	4.5	5	6.1	5.1	6.9
N fertilizer recommendation (kg per ha per year)	214.29	188.57	235.51	222.86	227.14	270
P fertilizer recommendation (kg per ha per year)	47.14	42	50.57	41.14	44.57	54
K fertilizer recommendation (kg per ha per year)	203.57	173.57	225	177.86	220.71	242.15

TABLE 4 Expert recommendations for cases 1, 2, and 3.

Subject	Case 1			Case 2			Case 3		
	Recommendations per hectare per year								
	N	P	K	N	P	K	N	P	K
Expert 1	275.75	47.5	-	246	42.5	-	246	42.5	-
Expert 2	285	38	171	221	51	221	238	51	221
Expert 3	250	45	230	245	443	225	260	51	240
Expert 4	289.5	15.05	180	275	25.07	224.1	298.5	25.07	211.65
Expert 5	280	99	297	229	81	243	171	102	307
Expert 6	266	38	171	221	51	221	238	51	221
CBR system	231.42	44	177.86	217.14	44.57	202.14	244.28	51.42	216.43
PCC	0.578	0.894	0.987	0.665	-0.178	0.939	0.612	0.431	0.883

TABLE 5 Expert assessment for cases 4, 5, and 6.

Subject	Case 4		Case 5		Case 6	
	LS	Value	LS	Value	LS	Value
Expert 1	Acceptable	3	Unsatisfactory	2	Unsatisfactory	2
Expert 2	Acceptable	3	Acceptable	3	Acceptable	3
Expert 3	Inadequate	1	Inadequate	1	Unsatisfactory	2
Expert 4	Acceptable	3	Effective	4	Effective	4
Expert 5	Unsatisfactory	2	Inadequate	1	Unsatisfactory	2
Expert 6	Effective	4	Effective	4	Effective	4

suggests a significant discrepancy in how each expert assessed the nitrogen recommendations.

- ICCa for P: The ICCa for P was very low (−0.003), indicating no consistent agreement between experts. This lack of agreement highlights the challenges in determining phosphorus levels, which are often more context-specific and sensitive to local soil chemistry.
- ICCa for K: The ICCa for potassium was also negative (−0.17), again indicating poor agreement. This could be due to expert's different approaches to addressing potassium levels under various conditions.
- The average ICCa for the three nutrients combined was also low, reflecting the overall discrepancy in expert opinions. These findings indicate that while experts provided valuable information, their recommendations often needed to be more consistent, likely due to the high variability and complexity of coffee fertilization practices. These discrepancies underline the need to incorporate more local

environmental data into the FRS to better align with expert knowledge.

Furthermore, for the final three cases, we calculated the ICCa for these categorical ratings, indicating poor agreement between experts (−0.03). The lack of consensus may indicate the subjective nature of these assessments, where factors such as individual experience, specific field conditions, and interpretation of the data provided may generate such discrepancy in the formation of expert opinions. The Notebooks used for the calculation of the ICCa, as well as the surveys and the expert's responses, are included in the supplementary data attached to this work, allowing the reproduction and verification of the results obtained.

Finally, by averaging the PCC values between the system's recommendations and those provided by the experts for the first three cases (1, 2, and 3), an average value of 0.646 was obtained. This result indicates a moderate agreement between the system's recommendations and the experts. On the other hand, for Cases 4, 5, and 6, in which the experts evaluated the system's recommendations using a Likert scale, the average of the ratings was 2.66, which falls between the Regular and Acceptable categories, with a slight inclination toward the Acceptable category. This result suggests that, although the system provides recommendations that are mostly seen as adequate, there are still areas for improvement. The PCC analysis and the use of LS reinforce the idea that the CBR system has good potential for fertilizer recommendation in coffee crops but still requires adjustments and greater incorporation of local contextual data to achieve greater alignment with the recommendations. These results provide a solid foundation for continued development and refinement of the system to improve its accuracy and applicability in coffee agriculture.

4 Discussion

The evaluation of the CBR system revealed essential insights into its performance in providing fertilization recommendations for coffee crops. Despite the system showing moderate to high correlation for some nutrients—particularly potassium—discrepancies between the system's outputs and expert recommendations highlight areas where improvement is needed. For instance, nitrogen and phosphorus showed variability across different cases, with a negative correlation for phosphorus in one of the evaluated cases. These findings suggest that the promising system still requires refinement to better capture the nuances of fertilization practices, particularly in regions like Cauca, where environmental factors and soil characteristics vary significantly.

The ICCa further highlighted the inconsistencies among expert evaluations, particularly for nitrogen and phosphorus. Low agreement among experts, as reflected by negative or near-zero ICCa values, suggests that the complexity of coffee fertilization may lead to divergent opinions depending on individual experience and local knowledge. This is consistent with previous studies showing similar challenges in developing uniform fertilizer recommendations across diverse agricultural contexts. For instance, Kumar et al. (2019) and Suchithra and Pai (2018) emphasize integrating local environmental data, such as soil pH, organic matter content, and crop-specific conditions, into intelligent systems to improve recommendation accuracy.

These results reinforce the need for further development of the CBR system. Incorporating additional variables such as organic matter, crop age, the nutrients exported by the future harvest, and more detailed local soil and climate data could improve the alignment between the system's recommendations and expert opinions. Similar improvements have been suggested in works like Wickramasinghe et al. (2019), where sensor-based data collection has been shown to enhance the precision of FRS.

Considering these findings, future iterations of the system should focus on increasing its adaptability to different environmental conditions. This could involve integrating real-time sensor data and expanding the knowledge base with region-specific agricultural data, similar to the approaches seen in McFadden et al. (2018) and Ren and Lu (2012). By doing so, the system can move toward providing more contextually relevant recommendations that better align with expert knowledge while maintaining flexibility across various regions and agricultural practices.

5 Conclusions

Recommender systems have provided multiple insights into various crops, allowing farmers to improve production, mitigate risks such as diseases and pests, improve decision-making in various agricultural practices, and even reduce associated environmental impacts. However, their implementation in real-world environments must be enhanced by technological limitations in capturing the data necessary for these systems to function effectively, especially in the Colombian region. In this sense, this research proposed an RS that, unlike existing works, is based on expert knowledge obtained through interviews with domain experts and scientific research from Colombian private institutions related to coffee cultivation. The approach's recommendations are based solely on current crop status and climatic conditions; rather than historical soil information or crop production records. Consequently, the implemented system successfully addressed the problem of the scarcity of data needed to generate recommendations. It was demonstrated through evaluation that the results obtained were close to the expert's suggestions, but there were many corrections regarding more information to be analyzed. To increase the case base and the agroclimatic variables studied. Considering that the tests carried out reached the laboratory level, it is an initial prototype that can receive many improvements in the future.

Regarding implementing the system, it was determined that leveraging expert knowledge in agriculture is essential for crops with limited data availability, especially when it is challenging to access historical data on crucial parameters such as climate, crop management, and soil. The CBR, which has proven effective in other application domains, demonstrated in this study that its application in agriculture, together with the participation and collaboration of experts, can contribute to supporting the sustainability of small farmers.

Furthermore, the knowledge base built can be important for future research in coffee cultivation, as it establishes a mechanism to automatically identify relevant variables in coffee cultivation by

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analyzing the importance and meaning of soil, crop, and climate variables. This allows us to determine which variables are more appropriate or have greater weight than others.

6 Future works

Considering the research opportunities that arise with the development of this research project, the following future work is proposed.

The current FRS provides suggestions solely for the quantity and frequency of fertilizer application. However, an essential aspect of fertilization management that remains to be explored is the type of fertilizer. Future work could focus on refining the recommendations by considering the types of fertilizers available in the market, which vary in cost and nutrient composition. In this sense, a key enhancement would be the ability of the system to recommend specific fertilizer formulations based on the crop's nutrient requirements at different growth stages. For example, based on the results of this study, the IoT system could recommend an initial application of a complete NPK fertilizer that covers the phosphorus requirement at flowering, followed by a second application of urea + KCl to meet the nitrogen and potassium needs during the fruit growth and filling stages.

In addition, developing a dashboard interface for farmers and domain experts to provide more detailed information beyond fertilizer quantities is proposed as a next step. This interface could offer early alerts related to fertilization, including analysis of seasonal changes and their impact on nutrient absorption and loss. It could also integrate soil condition monitoring, helping farmers optimize fertilizer application timing and effectiveness.

Although this study demonstrated that the system's recommendations were in line with those provided by experts, more research is needed to assess the long-term impact of these recommendations on coffee production. Future evaluations should be conducted over multiple years, tracking fertilization events, coffee yield, and quality. To that end, the recommender system could be complemented with automated data collection modules that monitor fertilization events and production outcomes, allowing feedback to be incorporated into the CBR system and improving its accuracy over time.

Finally, it is essential to mention that while this system was developed for coffee cultivation, the architecture and approach can be adapted for other crops. This system could be extended by modifying the case base to consider crop-specific characteristics to optimize fertilization practices for various agricultural contexts.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found in the article/supplementary material.

Author contributions

EL: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. JFCO: Conceptualization, Resources, Supervision, Validation, Visualization, Writing – review & editing. JCC: Conceptualization, Funding acquisition, Methodology, Project administration, Software, Supervision, Writing – review & editing. CF: Conceptualization, Formal analysis, Methodology, Supervision, Validation, Writing – review & editing.

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Conflict of interest

JFCO was employed by Ecotecma S.A.S.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Acuña, D. G. H. (2019). *Sistema de recomendación de libros basado en ontologías asociadas a tesauros: El caso de la biblioteca de la facultad de ingeniería de sistemas e informática de la universidad nacional mayor de san marcos* (Bachelor's thesis). Universidad Nacional Mayor de San Marcos.

Arcila P., J., Farfán V., F., Moreno B., A., Salazar G., L. F., and Hincapié, G. E. (2007). "Densidad de siembra y productividad de los cafetales," in *Sistemas de producción de café en Colombia, Volume 1 of* Fitotecnia, Prácticas de cultivo, Caficultura, 1 Edn. (Chinchiná, Caldas: Editorial Blanecolor Ltda.), 131–144.

Bilen, C., El Chami, D., Mereu, V., Trabucco, A., Marras, S., and Spano, D. (2023). A systematic review on the impacts of climate change on coffee agrosystems. *Plants* 12:10102. doi: 10.3390/plants12010102

Boregowda, N., Jogigowda, S. C., Bhavya, G., Sunilkumar, C. R., Geetha, N., Udikeri, S. S., et al. (2022). Recent advances in nanoremediation: carving sustainable solution to clean-up polluted agriculture soils. *Environ. Pollut.* 297:118728. doi: 10.1016/j.envpol.2021.118728

Chaves, P. A. (2016). Grado de aceptación e implementación de las tic por campesinos agrícolas con vocación cafetera en el municipio del tambo-cauca (Master's thesis). Universidad Nacional Abierta y a Distancia UNAD, Popayán, Colombia.

Cholissodin, I., Dewi, C., and Eunike Endariahna Surbakti (2016). "Integrated ANN and bidirectional improved PSO for optimization of fertilizer dose on Palawija plants," in *2nd International Conference on Science in Information Technology (ICSITech)* (Balikpapan: IEEE), 193–197.

Chougule, A., Jha, V. K., and Mukhopadhyay, D. (2019). "Crop suitability and fertilizers recommendation using data mining techniques," in *Progress in Advanced Computing and Intelligent Engineering, Vol. 714*, eds. C. R. Panigrahi, A. K. Pujari, S. Misra, B. Pati, and K.-C. Li (Singapore: Springer Singapore), 205–213.

Drechsel, P., Marjani Zadeh, S., and Salcedo, F. (2023). *Water Quality in Agriculture: Risks and Risk mitigation*. Rome: FAO.

Farfán V. F., and Mestre M. A. (2004). Manejo del sombrío y fertilización del café en la zona central colombiana. *Cenicafé*, 330:1–8. doi: 10.38141/10779/0330

FNC (2013). *Manual del cafetero colombiano, Vol. 2, 1 Edn*. Chinchiná, Caldas: LEGIS.

Gabel, T. (2010). *Problem Solving By Case-Based Reasoning*. Friburg: Machine Learning Lab—Friburg University.

Gast, F., Benavides M. P., Sanz U. J. R., Herrera P. J. C., Ramírez Builes, V. H., Cristancho A. M., et a;. (2013). "Gestión del riesgo agroclimático. Vulnerabilidad y capacidad de adaptación del sistema de producción de café," in *Investigación y tecnología para la sostenibilidad en la agricultura, Vol. 1 of* Manual Del Cafetero Colombiano (Chinchiná: LEGIS), 91–114.

Hossain, M., and Siddique, M. N. A. (2020). Online fertilizer recommendation system (OFRS): a step towards precision agriculture and optimized fertilizer usage by smallholder farmers in Bangladesh. *Eur. J. Environ. Earth Sci.* 1, 1–9. doi: 10.24018/ejgeo.2020.1.4.47

Howland, F. C., Muñoz, L. A., Staiger, S., Cock, J., and Alvarez, S. (2015). Data sharing and use of ICTS in agriculture: working with small farmer groups in Colombia. *Knowl. Manag. Dev. J.* 11, 44–63.

Islam, T., Uddin, R., Rizan, R., Tusher, Y., Hossain, M. A., and Galib, S. (2020). Nitrogen fertilizer recommendation for paddies through automating the leaf color chart (LCC). *Int. J. Adv. Comput. Sci. Appl.* 11, 745–752. doi: 10.14569/IJACSA.2020.0110891

Jiang, W., Xing, Y., Wang, X., Liu, X., and Cui, Z. (2020). Developing a sustainable management strategy for quantitative estimation of optimum nitrogen fertilizer recommendation rates for maize in Northeast China. *Sustainability* 12:2607. doi: 10.3390/su12072607

Kitchenham, B. A., and Charters, S. (2007). *Guidelines for Performing Systematic Literature Reviews in Software Engineering. Technical Report EBSE 2007-001*. Keele: Keele University and Durham University Joint Report.

Kolodner, J. L. (1992). An introduction to case-based reasoning. *Artif. Intell. Rev.* 6, 3–34.

Kumar, A., Kumar, A., De, A., Shekhar, S., and Singh, R. K. (2019). IoT based farming recommendation system using soil nutrient and environmental condition detection. *Int. J. Innov. Technol. Explor. Eng.* 8, 3055–3060. doi: 10.35940/ijitee.K2335.0981119

Lenka, S., S, R., Coumar, V., Dotaniya, M., and Saha, J. (2016). *Impact of Fertilizers Use on Environmental Quality*. (Kalyani: Bidhan Chandra Krishi Viswavidyalaya), 11.

León-Burgos, A. F., Unigarro, C., and Balaguera-López, H. E. (2022). Can prolonged conditions of water deficit alter photosynthetic performance and water relations of coffee plants in central-west Colombia? *South Afr. J. Bot.* 149, 366–375. doi: 10.1016/j.sajb.2022.06.034

Martín Alonso, G. M., Pérez Díaz, A., Espinosa, R. R., González, C. B., Viñals Núñez, R., and Nualles, M. V. (2016). Comparison of two models of response to nitrogen doses in corn and coffee. *Cult. Trop.* 37, 155–164.

McFadden, B. R., Brorsen, B. W., and Raun, W. R. (2018). Nitrogen fertilizer recommendations based on plant sensing and Bayesian updating. *Precision Agri.* 19, 79–92. doi: 10.1007/s11119-017-9499-4

Miller, M. (2019). *The Basics: KNN for Classification and Regression*. Towards Data Science.

National Aeronautics and Space Administration (2017). *Technology Readiness Level Definitions*.

National Weather Service (2023). *NOAA's Climate Prediction Center*. College Park, MD.

Pozas, J. S. (2008). Fertilidad del suelo y nutrición del café en Colombia—Guia práctica. *Cenicafé* 32:45.

Puntel, L. A., Pagani, A., and Archontoulis, S. V. (2019). Development of a nitrogen recommendation tool for corn considering static and dynamic variables. *Eur. J. Agron.* 105, 189–199. doi: 10.1016/j.eja.2019.01.003

Qin, Z., Myers, D. B., Ransom, C. J., Kitchen, N. R., Liang, S., Camberato, J. J., et al. (2018). Application of machine learning methodologies for predicting corn economic optimal nitrogen rate. *Agron. J.* 110, 2596–2607. doi: 10.2134/agronj2018.03.0222

Ren, Z., and Lu, X. (2012). "Design of fertilization recommendation knowledge base and appllication," in *First International Conference on Agro- Geoinformatics (Agro-Geoinformatics)* (Shanghai: IEEE), 203–207.

Rodríguez-Espinosa, T., Papamichael, I., Voukkali, I., Gimeno, A. P., Candel, M. B. A., Navarro-Pedreño, J., et al. (2023). Nitrogen management in farming systems under the use of agricultural wastes and circular economy. *Sci. Tot. Environ.* 876:162666. doi: 10.1016/j.scitotenv.2023.162666

Sadeghian Khalajabadi, S. (2016). La acidez del suelo, una limitante común para la producción de café. *Cenicafé* 466, 1–12.

Sadeghian Khalajabadi, S. (2017). Síntomas visuales de deficiencias nutricionales en café. *Cenicafé* 478:12. doi: 10.38141/10779/0478

Sadeghian Khalajabadi, S., Osorio, H. G., and Suárez, E. A. (2015). Lixiviación de nutrientes en suelos de zona cafetera. *Prácticas que ayudan a reducirla*. 40, 1–36.

Sadeghian, S. (2008). Fertilidad del suelo y nutrición del café en Colombia : Guía práctica. *Boletín Técnico Cenicafé* 32, 1–44.

Sainju, U. M. (2017). Determination of nitrogen balance in agroecosystems. *MethodsX* 4, 199–208. doi: 10.1016/j.mex.2017.06.001

Sànchez-Marrè, M. (2001). *Principles of Case-Based Reasoning*.

Shang, Y. (2005). "5—expert systems," in *The Electrical Engineering Handbook*, ed. W.-K. Chen (Burlington: Academic Press), 367–377.

Suchithra, M. S., and Pai, M. L. (2018). "Improving the performance of sigmoid Kernels in multiclass SVM using optimization techniques for agricultural fertilizer recommendation system," in *Soft Computing Systems, Vol. 837*, eds. I. Zelinka, R. Senkerik, G. Panda, and P. S. Lekshmi Kanthan (Singapore: Springer), 857–868.

Sujithra, T., Thanjaivadivel, M., and Durai, S. (2019). Fertilizer recommendation system for coconut cultivation. *Int. J. Civ. Eng. Technol.* 8, 813–819.

Sumaryanti, L., Lamalewa, L., and Istanto, T. (2019). Implementation of fuzzy multiple criteria decision making for recommendation paddy fertilizer. *Int. J. Mech. Eng. Technol.* 10, 236–243.

Sylvester, J., Valencia, J., Verchot, L. V., Chirinda, N., Romero Sanchez, M. A., Quintero, M., et al. (2020). A rapid approach for informing the prioritization of degraded agricultural lands for ecological recovery: a case study for Colombia. *J. Nat. Conserv.* 58:125921. doi: 10.1016/j.jnc.2020.125921

Valdivielso, A. (2020). *Qué es la escorrentía*. iAgua.

Vélez-Vallejo, R. (2022). *Informe del gerente—90 congreso nacional de cafeteros. Technical Report*. Bogotá: Federación Nacional de Cafeteros de Colombia.

Vieira Fontoura, S. M., Viero, F., Moraes, R. P. D., and Bayer, C. (2017). Nitrogen fertilization of no-tillage winter cereals in the South-Central Region of Paraná, Brazil. *Revista Brasileira de Ciência do Solo* 41, 1–16. doi: 10.1590/18069657rbcs20170009

Wickramasinghe, C., Lakshitha, P., Hemapriya, H., Jayakody, A., and Ranasinghe, P. (2019). "Smart crop and fertilizer prediction system," in *2019 International Conference on Advancements in Computing (ICAC)* (Malabe: IEEE), 487–492.

World Bank (2022). *Agriculture (% of GDP)—Colombia | Data*. World Bank Group.

Zhang, H., Zhang, L., Ren, Y., Zhang, J., Xu, X., Ma, X., et al. (2011). "Design and implementation of crop recommendation fertilization decision system based on WEBGIS at village scale," in *Computer and Computing Technologies in Agriculture IV, volume 345*, eds. D. Li, Y. Liu, and Y. Chen (Berlin, Heidelberg: Springer), 357–364.

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Conceptualizing the governance challenges for food system transformation

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Approaches to food systems are receiving increased attention because they provide a more holistic perspective on the organization of food production and supply and on how to promote food safety, environmental sustainability, and equity. While the structure and complexity of food systems are widely acknowledged, efforts to understand their governance and possible challenges are just starting. We contribute to conceptualizing these challenges by harnessing the conceptual insights of multiple system governance frameworks. Conceptual and empirical lessons from these frameworks help to understand the possible challenges that may emerge when dealing with key features of modern globalized food systems. These include cross-spatial and temporal dynamics, managing common trade-offs across food system goals, and integrating narratives and policies when dealing with diverse stakeholders, sectors, and knowledge communities. We discuss the implications of addressing challenges that may arise in one or more of these key features, especially under the new governance paradigm in which modern food systems are embedded and in the presence of diverse paradigms and power asymmetries.

KEYWORDS

food systems, governance challenges, trade-offs, cross-spatial governance, temporal mismatches, integration

1 Introduction

In the multiple food system crises of deteriorating health, water resources, and climate (Rockström et al., 2020; Springmann et al., 2018; Swinburn et al., 2019), the demand for transforming food systems has grown internationally [FAO, IFAD, UNICEF, WFP, and WHO, 2018; High Level Panel of Experts on Food and Nutrition (HLPE), 2017]. Recognizing the failure of conventional policy-making to address these interconnected syndemic crises through siloed sectoral interventions (Swinburn et al., 2019), authors and practitioners are calling for more integrated approaches to food system challenges (e.g., De Brauw et al., 2019; Fanzo et al., 2013; Galluzzi et al., 2010; Leach et al., 2020; Ruben et al., 2018). However, despite increasing efforts to define, describe, and propose frameworks to analyze and/or design food system governance (e.g., Candel, 2014; High Level Panel of Experts on Food and Nutrition (HLPE), 2017; Delaney et al., 2018; Termeer et al., 2018; van Bers et al., 2019), the governance challenges that might be faced when engaging with the actual transformation of current food systems remain less defined. To contribute to addressing this knowledge gap, in the following section, we start by taking stock of a widely shared understanding of food systems and propose a working definition for analyzing governance challenges in the context of the systemic interconnections of globalized food systems. Despite existing suggestions for the way forward (e.g., adopting common indicators, Delaney et al., 2018; proposed governance arrangements, Termeer et al., 2017; or analyzing the politics of transformation, Béné and Abdulai, 2024), the possible governance challenges to achieve concrete food system transformation remain under-conceptualized. Our paper contributes to previous efforts to conceptualize food system governance challenges (e.g., Hospes and Brons, 2016; Van Bers et al., 2019) by using concepts and insights from the system governance literature that focus on complex systemic challenges in a variety of fields (e.g., water, energy, environmental policy, etc.) and by referring to real-world examples.

1.1 Food system governance

Food systems are defined by the High Level Panel of Experts (HLPE) as 'all the elements and activities that relate to the production, processing, distribution, preparation, and consumption of food, and the outputs of these activities, including socio-economic and environmental outcomes' [High Level Panel of Experts on Food and Nutrition (HLPE), 2017, p. 11]. This definition draws inspiration from the literature on systems (Bertalanffy, 1972; Rapoport, 1986) and its application to various domains, such as the environment (Hornberger and Spear, 1981), finance (Mayer, 1990), and management (Wilkinson and Dale, 1999). The concept of governance refers to the range of social processes and practices involved in 'solving societal problems and creating societal opportunities through interactions among civil, public and private actors' (Kooiman et al., 2008, p. 17). Building on both definitions, food system governance consists of the 'processes and actor constellations that shape decision-making and activities related to the production, distribution and consumption of food' (van Bers et al., 2016, p. 10).

Our conceptual contribution is organized around four challenges that emerge from the need for food system governance efforts to address temporal and spatial scales, trade-offs, and the call for integration of goals (Delaney et al., 2018; Pahl-Wostl et al., 2021). More specifically, this implies that food system governance challenges may emerge from tensions between their short-term operational characteristics (e.g., providing food daily around the globe) and the demand for a long-term horizon to ensure environmental, social, and economic sustainability (Parsons and Hawkes, 2018). The second challenge refers to the need to address cross-spatial scale dynamics given the teleconnectivity in food value chains. A concrete example of this is that activities to boost production in a specific landscape may be accompanied by environmental pollution in that area while, at the same time, generating negative or positive externalities in distant locations (D'Odorico et al., 2018).

Related to the above system dynamics, the third characteristic of modern globalized food systems is the presence of divergent values of stakeholders that prioritize different interventions, which may lack win-win opportunities and even result in difficult trade-offs. For example, some stakeholders may prioritize food system activities that perform well in terms of emission reductions for future generations but poorly in terms of other outcomes, such as employment generation, which may be a highly valued priority for another stakeholder. A final fourth characteristic refers to the complexity that emerges from the need for multiple and diverse stakeholders to negotiate, find compromise, and/ or integrate decisions, policies, or activities to minimize trade-offs and conflicts and/or maximize synergies and investments that produce shared desirable outcomes. An example of such integrative efforts is those of stakeholders focused on sustainable dietary transformative interventions, which bring together narratives, problems, and possible solutions from diverse policy areas such as agroecology, nutrition, biodiversity conservation, climate change mitigation and adaptation, and food value chain businesses. In the following section, we draw on different frameworks to conceptualize the governance challenges emerging from each of these four food system characteristics.

2 Food system governance challenges

2.1 Cross-spatial dynamics

Cross-spatial dynamics involve mobile social actors, border-crossing material flows (Herring, 2015b; Oosterveer, 2007), economic and administrative transactions across scales (e.g., from the local to the global), and the global distribution of economic, environmental, and social outcomes of food production and consumption (Mac Donald et al., 2015). In spatially-distributed modern food systems, food value chain activities (i.e., production, distribution, transformation, and consumption) happen in distant regions and often in different countries. This may pose significant challenges in identifying which legitimate authority (e.g., to establish and enforce rules, resources, etc.) can address negative food systems externalities (e.g., obesity, water pollution, unemployment, etc.). The literature on Multi-Level Governance (MLG) suggests that initiatives to manage cross-spatial scale system dynamics may face two types of tensions (Hooghe and Marks, 2003; Piattoni, 2009). First, tensions between the national state and sub-national levels arise as, depending on the level of centralized control over resources, the former may dictate uniform rules and regulations across all sub-national landscapes, thus de facto overlooking the specific concerns of locally affected inhabitants. An example of this is the tensions that emerged around the 1972 Federal Insecticide, Fungicide, and Rodenticide Act, which gave regulatory authority to the US federal government, thus hampering the ability of local authorities to respond to local health concerns regarding soil and water pollution (Centner and Heric, 2019). Second, tensions between the national state and the international level, as the former is mandated to protect its citizens from the negative externalities of international trade (Keleman et al., 2009), although it may face (legal) obstacles imposed by international trade agreements. A concrete example is the trade barriers and/or subsidies that a country may adopt to protect the national market for crops that represent key national dietary staples, but which might be imposed at international level by organizations like the World Trade Organization (WTO). An example of this struggle for authority between national governments and international organizations is the tensions that emerged between national priorities set in the WTO Doha Round of international agricultural trade negotiations (Farsund et al., 2015). National tensions emerged between demands for national protective measures to ensure internal food security, on one side, and pressures to maintain the global integrity of free trade principles and eliminate trade barriers and subsidies, on the other (Margulis, 2014). In this respect, the MLG literature suggests that locating authority to address negative externalities (e.g., pollution, food insecurity) of the food system can be challenging because of uncertainties and conflicting interests or paradigms regarding what is the most effective institutional design in terms of optimizing the use of public resources at a specific administrative level, but also in terms of ensuring accountability to respond effectively and timely to the concerns of affected parties (e.g., water users affected by pollution in a specific landscape or food insecure communities). A concrete example of how these tensions have been addressed in international trade comes from the reconfiguration of the locus of authority that the G20 countries have led by creating the G20 agriculture ministerial groupings as an additional institutional space that gathers their national authorities to set global priorities in agricultural reform and food security beyond the international role of the WTO (Margulis, 2014).

2.2 Cross-temporal dynamics

Two types of cross-temporal dynamics can emerge from governance efforts to transform food systems, namely, temporal misalignment in socio-ecological systems and temporal (mis-) alignment in societal change dynamics. The misalignment between social and ecological systems arises from the mismatch between the temporal discounting preferences (i.e., "preference for immediate gains at the expense of future outcomes"; Ruggeri et al., 2022) that different social groups have for food system outcomes, such as ensuring daily food provisions for growing (short- and medium-term) demand (Herring, 2015a; Nguyen et al., 2019; Porkka et al., 2013), and the imperative to ensure the long-term sustainability of natural ecosystems. This becomes entangled in governance challenges as some social groups may be more aware and share values that prioritize nature cycles and support activities that conserve the long-term natural dynamics of ecosystem functioning (e.g., agroecology or agrobiodiversity conservation movements; Gliessman, 2013) or because their livelihoods are strictly dependent on nature's services (Vignola et al., 2015). In contrast, other social groups may share values and prioritize short-term (financial) benefits (Frederick et al., 2002) and activities that promote a faster rate of land exploitation *in situ* (Smith et al., 2016) or to replace land depletion in one area by sourcing from distant landscapes (Burgers and Susanti, 2011; Hall, 2011; Margulis et al., 2013). In the latter case, however, preferences for short-term financial benefits may promote ecosystem degradation and, as a consequence, increase the burden of these unsustainable activities on future generations.

This discount rate mismatch permeates modern, highly-financialized food systems (Clapp, 2017) as, on one side, social movements call for and promote food system alternatives for a sustainable future, and on the other side, powerful food trade corporations operate in the financialized food system narrative in which time is money, so that the more resources are extracted, transformed, and marketed per time unit, the greater the perceived benefits. The consequences of this economic benefit-based temporal mismatch are clearly exemplified by the increasing adoption of the Discounted Cash Flow (DCF) model in African (Ducastel and Anseeuw, 2013), European, and US (Clapp and Isakson, 2018) investments. As shown by these authors, this financialization trend has been accompanied by, on one side, a transformation of agricultural products into financial assets to be valued based on Present Value Discount Rates and risk assessment of cash return flows, and, on the other side, a significant increase in the vulnerability of ecosystems, food workers, consumers and producers.

The second *temporal (mis-)alignment in societal dynamics* emerges from the temporal misalignment between the maturity level of an innovation introduced to promote food system transformation, and the time needed to create the enabling conditions and windows of opportunity to mainstream it at the scale required. The literature on sustainable transition theory has conceptualized this temporal dynamic of structural system transformation (Geels, 2011), suggesting the importance of synchronizing investments to scale up innovations (e.g., new technologies, ideas, new framings of problems, etc.) with the identification of opportunity windows offered by increasing societal demand (e.g., for healthy and sustainable food) and the presence of enabling conditions and a sufficient level of maturity of the innovation. The maturity of a potentially transformative food system innovation may depend on whether (i) learning processes for its uptake are well established and supported by powerful actors, and (ii) there is evidence of an expectation for further improvement and sufficient adoption in the system (Geels and Schot, 2007). An example of this dynamic is the growing demand for organic food from health and environmentally conscious consumers, who are urging markets to expand the supply of safe, healthy and/or environmentally sustainable food (Sahota, 2009; Smith et al., 2016; Spaargaren et al., 2012). This offered a window of opportunity for an alternative and relatively small food niche led by bottom-up movements to be upscaled and captured by powerful actors in food distribution and retail systems (e.g., supermarket chains) that could provide well-established enabling conditions (logistics, labeling, marketing) for fast scale-up (Reardon and Hopkins, 2006; Spaargaren et al., 2012).

2.3 Managing trade-offs

Governance of food systems entails intricate decision-making processes (Hooghe and Marks, 2003; Stoker, 1998) that require the navigation of synergies and trade-offs (Jessop, 2003) between diverse food system objectives and mandates that are stewarded over by stakeholders operating in different food system components (e.g., environmental conservation, public health, value chain segments, etc.). Addressing trade-offs and synergies in food system governance may be a challenging process, not only given the diversity of values and perspectives regarding priorities and solutions (e.g., between advocates of agro-ecological vs. industrial intensification) but also because of different views regarding the principles and norms that should guide the assessment of alternatives. From the perspective of Meta- Governance (MG; Kooiman and Jentoft, 2009), values reflect "the most general and fundamental notions" about what should be prioritized in evaluating the alternatives, while norms and principles reflect the "general notions of what is right or wrong" regarding, respectively, the governance process (e.g., what knowledge should be used, who should participate, etc.) and what rules are considered acceptable (Kooiman and Jentoft, 2009, p. 824).

The extent of the challenge for efforts to transform food system governance may depend directly on the extent to which underlying values are made explicit and shared among actors in a transparent way (IPBES, 2022) and/or are measurable or comparable. For example, when evaluating innovation in agricultural practices, one societal group may prioritize the intrinsic value of nature as a parameter to judge the performance of the practices, while another social group may prioritize other dimensions that may be difficult to compare with the previous (e.g., employment and/or financial returns) (Piñeiro et al., 2020). From a normative perspective, this requires a reflexive governance process to ensure a collectively shared understanding of what norms and principles are acceptable for the decision process (e.g., in rule setting, location of authority, etc.) to manage plural values regarding alternative food system solutions that are debated and agreed upon. In theory, governments can promote a reflexive process through regulations and/or by supporting the creation and maintenance of social capital and social networks, gathering information and monitoring governance outcomes, and ensuring a power balance in negotiations (Jessop, 2003). In reality, decision-making in multi-stakeholder fora addressing food system issues is often dominated by large corporations and lacks mechanisms to make value differences explicit, address conflicts, and reduce power asymmetries (IPBES, 2022).

According to the governance literature, the willingness of governments and other actors to engage and address complex problems in a transparent, inclusive, and reflexive manner may depend on a variety of institutional, social, and/or cultural contextual conditions. As shown in the literature on food system governance, these conditions may include the extent to which pre-existing conditions facilitate consensus-building processes (e.g., collaborative experiences, trust, conflict, etc.), the presence of adequate leadership, expectations and capacities for engagement with civil society and the private sector, and, finally, the extent to which actors' values regarding food system alternatives are measurable and/or comparable (Ansell and Gash, 2007; Béné et al., 2019; Gillespie et al., 2019a). Examples from the recent IPES-Food (2023) suggest that international and national regulations to curb corporate influence have been insufficient while a variety of bottom-up innovations (e.g., participatory public budgeting, sub-national food councils and cooperatives, municipal food initiatives) around the world provide space to explicitly address diverse values and power asymmetries.

2.4 Integration challenges

As suggested by authors focusing on transformative governance for sustainable development (Visseren-Hamakers et al., 2021), transformative food system governance implies addressing integration challenges emerging from the variety of stakeholders involved, the lack of a pre-established shared vision and objectives, and the associated ambiguity regarding causes, priorities and possible solutions (Béné et al., 2019; Edwards et al., 2024). Adopting a food system lens implies that the implementation and the outcomes of a specific food system intervention/activity (e.g., promoting the production of healthy food) should complement and/or be consistent with those of other food system activities (e.g., minimizing the risk of water scarcity) in a way that maximizes synergies and minimizes trade-offs (de Brauw et al., 2019). In the formal policy-making context of an ideal Weberian modern state, sectoral policies set rules, norms, principles, and (dis-)incentives to optimize the use of resources and promote consistent and coherent interventions for the common good (e.g., healthy and climate-resilient food production). However, depending on the formal and/or informal policy-making environments in which these alignment processes are actually embedded in the real world, governance processes to integrate different food system activities can be more or less challenging. Conceptual insights from the literature on Environmental Policy Integration (EPI; Jordan and Lenschow, 2010) suggest that we can identify at least two major challenges within the formal sectoral policy-making context that may hamper integrative efforts across food system activities.

First, efforts to promote integration across important food system policy domains (e.g., nutrition, agriculture, land and water management, climate change mitigation and adaptation) may have to face significant resistance to change, as diverse stakeholder values and interests may determine how the distribution of benefits and costs is perceived to be (un-)evenly distributed across society. A clear example of governance challenges emerging from undealt-with diversity of values and interests is the mass protests by farmers in the Netherlands in 2022. These tensions may have resulted from the unresolved conflict (e.g., possibly worsened by poor communication, hidden political interests, etc.) between nature conservation policies and farmers' values regarding the security of their livelihoods and their perception of unfair problem identification and proposed solutions (Resnick and Swinnen, 2023).

Second, cross-sectoral policy integration requires dealing with different epistemic communities, professional languages and narratives. In the case of food systems for example, these differences may emerge between the epistemic communities of nutritionists, water managers, agronomists, and climate experts. Efforts to bring these epistemic communities together to design food system policy integration efforts may face challenges in finding common ground on main problems, investment priorities, and solutions.

EPI literature suggests that in countries with siloed sectoral policy-making traditions, it may be difficult to devise specific cross-sectoral legislation, possibly due to a variety of reasons that may include interests in maintaining sectoral resource control, unaddressed epistemic and semantic differences regarding problem definition and solutions, and how effectiveness indicators are stated and monitored. In such contexts, it may be easier to promote shared, broadly defined cross-sectoral policy statements, for example, on generally defined healthy and sustainable food production than specific cross-sectoral legislation (Bouwma et al., 2018). In this context, overarching formal mandates to promote food system policy integration may face significant challenges to guarantee legitimate authority to address different values and narrative domains across sectors. In this respect, evidence from the food system governance literature suggests the importance of embedding food system transformation efforts within contexts by identifying opportunities within existing institutional structures and cultures and building on existing leadership (e.g., policy champions, entrepreneurs, etc.). For example, evidence from an analysis of efforts to promote inter-sectoral integration between agricultural and nutrition policies in Southeast Asia shows that in the absence of legal frameworks and clear mandates to support formal cross-sectoral authority, collective and individual leadership, political commitment, and accountability can be crucial (Gillespie et al., 2019b).

With the increasing role of non-governmental actors (e.g., private, civil society, academia, etc.) in food policy-making processes under the New Government Paradigm promoted in the 1990s (Durant et al., 2004), informal policy-making (i.e., beyond formal authority institutions; Reh, 2012) in multi-actor networks has become wide spread common in modern globalized food system governance (Oosterveer, 2006). Here, the literature on Network Governance (NG) (Jones et al., 1997; Provan and Kenis, 2008) can help to understand the types of challenges that can possibly be faced by food system governance efforts. Food system governance networks can be understood as interconnected (groups of) actors engaging in open-ended but socially binding forms of coordination to achieve goals that they cannot achieve on their own. These networks connect a variety of actors (State, NGOs, academics, private sector, etc.) through the exchange of products and services in value chains (e.g., food producers, distributoers, transformers, retailers and consumers) and/or because they may have a common stake in certain food system outcomes (e.g., nature conservation, climate change mitigation, nutrition, etc.). Examples are the numerous sustainable food certification schemes in which leading agents invest in building multi-actor networks from diverse social groups (e.g., scientists, policy-makers, and NGOs across scales and countries) and connect actors from production activities all the way to consumers (Oosterveer, 2006; Oosterveer, 2015a). Conceptual insights from the literature on network governance (Provan and Kenis, 2008) highlight the importance of maintaining a good reputation in networks. This implies, for example, that agents leading certification schemes must dedicate significant attention and resources to ensuring and promoting a generalized perception that their network actions are legitimate in the eyes of the consumers while being consistent with norms, values, beliefs, and accepted network definitions (e.g., of healthy and/or sustainable food products).

Considering the broad and informal policy-making context of large, cross-scale and cross-sector networks of actors in modern food systems, ensuring legitimacy in shaping and/or maintaining the coherence and value identity of a network may be significantly challenging. Largely cited authors in the Network governance literature (Provan and Kenis, 2008) pointed out that the difficulty (especially in large networks) in addressing this challenge may depend on the trust and (tacit or explicit) agreement among network members to achieve common goals through a given collaborative network arrangement for food system governance (e.g., who moderates/leads the network, what value identities and narratives are accepted). More recent reviews of the network governance literature (Wang and Ran, 2023) expand on this by suggesting that with larger and more stakeholders-diverse networks, complexity, and uncertainty increase, affecting network effectiveness in, for example, achieving a desired outcome (e.g., securing the reputational goods of a food certification scheme) and creating and/or maintaining a common identity. This may require food system governance network leaders to invest in efforts to maintain internal and external network legitimacy. This is confirmed by evidence from food policy networks showing how network leaders invest in efforts to build trust and legitimacy internally among food system actors who identify and share goals and values (e.g., as expressed through network identity) (den Boer et al., 2023; Oñederra-Aramendi et al., 2023). Network leaders also invest in building trust and legitimacy to bridge and interact with other networks (e.g., with departments and decision-makers in other sectors or administrative levels) and/or to seek support (e.g., funding, visibility, etc.). Tensions around legitimacy may arise as food system actors have to balance between their desire to keep their values and identity (e.g., corporate reputation; Yeoman and Santos, 2019) on one side, and their need to interact with larger networks (to achieve the intended outcomes) on the other. This may be especially important for large food corporations, given the ongoing trend not only to promote and strengthen their own individual corporate social reputation but also to expand the demand for reputation to the whole value chain (e.g., the ongoing initiatives of the task force on nature-related financial disclosures[1]). This is to ensure that all its members (i.e., across the value chain) abide by the network identity values and/or do not threaten (e.g., through unacceptable practices that undermine the credibility of food certification schemes) the reputation of the value chain network in the food market (Yeoman and Santos, 2019). This governance challenge may be common in global food systems and it may require building trust and legitimacy in food system governance networks, to support spaces of authority and food network leadership that differ from the current situation.

Indeed, more than 70 % of actors involved in multi-stakeholder network initiatives around the globe belong to the private sector (i.e., transnational corporations, business associations and consulting firms), for which reputational goods are also highly important due to their high centrality in global food governance networks (Van Den Akker et al., 2024). On the other side, although civil society actors are largely under-represented in multi-stakeholder initiatives (Van Den Akker et al., 2024), a recent systematic assessment of transformative food system governance initiatives (Rudnick et al., 2019) shows that they have a higher degree of legitimacy with local communities and, if supported by committed and resourceful local administrations, can embed and build long-term commitment to improving food system performance.

3 Discussion and conclusions

The concepts emerging from the various governance analytical perspectives presented above are relevant for understanding food system governance challenges (e.g., cross-spatial and temporal mismatches, trade-offs and integration challenges). However, in order to understand their relevance to food system transformation, it is important to consider that the challenges they help to understand rarely occur in isolation. Rather, many examples in modern food systems show that the closely interrelated nature of these challenges can translate them into concrete obstacles to real transformation. For example, integration across policy domains can imply negotiating with complicated trade-offs as the values of food system policy domains differ greatly and may not be comparable (e.g., conserving biodiversity, generating employment, guaranteeing healthy diets). Similarly, addressing trade-offs may also become difficult and may require significant investment in scientific debates and public deliberations due to competing/conflicting network identities such as, for example, around technically complex issues such as Genetic-Modified-Organisms (Hoppe and Turnbull, 2023), pesticide use (Hauck et al., 2016), and labeling (Guthman, 2007). Recent developments in the transparency, availability, and accessibility of food system data can not only support efforts to identify and address stakeholder value trade-offs but can also open up opportunities to build synergies and even, with adequate leadership and communication, expand networks and build support for transformation (Haddad, 2023).

1 https://tnfd.global/

Finally, given the blurred spatial boundaries and dispersed decision-making power of globalized food value chain networks, it may be difficult to identify where real authority is or should be located when dealing with environmental problems such as water pollution, deforestation, etc. More specifically, this may be particularly the case for globalized food networks, where authority and centrality in decision-making are strongly influenced by transnational corporations that operate typically from power centers that are distant from where environmental externalities occur (Van Den Akker et al., 2024). However, the environmental governance literature, which focuses on the influence of Global Production Networks on land use planning decisions for the conservation of ecosystem services in the Amazon landscape (Urzedo et al., 2020), shows possible ways to address these challenges. These authors found that despite their influential position in the global food trade, the power of large food corporate networks can be counterbalanced by locating authority at the state level as the ultimate promoter of ecosystem services and by opening up the networks to participation by national unions and environmental movements.

We argue that two additional challenges cut across all the ones we discussed above, namely, paradigm diversity and power asymmetries. As the 'deepest set of beliefs about how' a system works (based on: Meadows, 1999, p. 17), paradigms are important in shaping the perspectives of stakeholders and their ways of managing challenges. In general, paradigms are very difficult to change as they can form part of the identity of actors (Achrol, 1996) and become embedded in the routinized ways-of-doing of existing organizations until they become actual lock-ins to food system transformation (Geels, 2014; de Krom and Muilwijk, 2019; Kay, 2005). Thus, even if alternative paradigms for sustainable food systems are emerging in some food networks (e.g., agroecology, protein transitions, etc.), changing the dominant paradigm of modern and globalized food systems remains difficult (Bush, 2010; Kuokkanen et al., 2017; Parker and Johnson, 2019). Evidence suggests that even in countries where sustainable food system innovations are high on the political agenda and embedded in institutional structures, "business as usual" and "technological optimism" narratives still continue to dominate the debate (de Krom and Muilwijk, 2019; Thompson and Scoones, 2009), leaving little space for profound transformations (e.g., agroecological transitions). Then, governance efforts aimed at transforming food systems may have to contend with the resistance of agent networks that embrace paradigms oriented to maintain important features of the status quo such as, for example, the dominance of large-scale distribution (Burch and Lawrence, 2005), the financialization of food value chains (Clapp, 2017), the distribution of agricultural inputs (e.g., fertilizers, seeds, etc.) or agrochemical-intensive practices (Clapp, 2021).

The challenges of promoting alternative paradigms (e.g., to change the current distribution of benefits and costs) may be directly related to the extent of power asymmetry that exists in a specific food system intervention context (Anderson et al., 2019; De Schutter, 2017; El Bilali, 2019; Leach et al., 2020). Power asymmetries do not only relate to unequal access to economic and administrative resources but also to differences in positions within the (global) flows and networks of globalized food systems (Castells, 2009; Mol, 2010).

In this respect, the four categories of power in a network society (Castells, 2009) provide insights into the possible mechanisms through which power can emerge as a challenge in transforming food systems. The first form is *networking power*, which refers to the power to include some collectives and individuals and exclude others. This can take the form of a power actor being able to include producers in supply chain networks that are aligned to certain requirements (e.g., use of specific inputs and practices) and exclude others (who do not abide by these requirements) by using their structural power positions in value chain relations (Dicken et al., 2001). For example, organizations that set food standards may impose the adoption of specific requirements and procedures if they do not provide support and resources, de facto excluding producers who, due to contextual conditions, may not be able to abide by these certification requirements (Béné, 2005; Samerwong et al., 2017). The second, *Network power*, refers to the ability to impose rules, narratives, forms, and protocols of coordination and communication such as, for instance, those regarding food quality standards in a particular supply chain (Murdoch et al., 2000) affecting all its actors independently from their location in the network. The third, *Networked power*, is the relative power of one network over another. A particular network may impose its foundational values on another network. For example, in the modern financialized food system (Clapp, 2014), financial network nodes (e.g., banks, fiscal havens, etc.; Galaz et al., 2018) exert tremendous power (e.g., by imposing a monetary return paradigm) over ecosystem management decisions with respect to networks that advocate nature conservation or social equity values through certified (fair, organic, sustainable, etc.) products. Finally, as the ability to actually build networks, organize them, and manage their connections with other networks, *network-making power* is especially relevant when aiming to create new narratives, shift existing goals and paradigms and transform food systems, for example, by engaging other powerful networks.

Two types of network positions, defined in terms of the degree of centrality and the extent of cross-network brokering, can be important for network-making power, namely: programmers and switchers.

Programmers can be agents of any type who have a highly central position in a network and the ability to (re-)program narratives, goals, and standards that are accepted by a network in the making (Castells, 2009: 45). Switchers are agents who have a cross-bridging power to connect and ensure 'cooperation with other networks (e.g., by linking goals and combining resources; Castells, 2009: 45) while excluding other competing networks. An illustration of network-making power in global food systems is the Roundtable on Sustainable Palm Oil (RSPO), which defined (i.e., as a programmer) sustainability requirements for producing and trading this commodity, which ensured greater private sector control over the social and environmental standards to be followed. At the same time, given the lack of bridging agents (switchers) in the RSPO network, it remained difficult to link this private sector-dominated network with government networks in Indonesia and Malaysia (Oosterveer, 2015b).

The complexity, inter-relation, co-occurrence, and inherent context-dependency of the different challenges that may emerge (Juri et al., 2024), suggest that food system transformation can be understood as a complex and non-linear process of disruptive change over a period of several decades (Loorbach et al., 2017). This also suggests the importance of moving away from the naïve belief in one-size-fits-all type initiatives that focus on the effectiveness and efficiency of a specific technological solution or standard models of policymaking. Rather, it suggests the need to recognize the multifaceted nature of food systems (e.g., often global value chains coexist with local markets; Gaitán-Cremaschi et al., 2018) and that food system transformation should happen through multiple pathways (Scoones et al., 2020), not all of which are equally feasible or acceptable to all parties (Weber et al., 2020). According to some scholars (Singh et al., 2023), an important pathway to transform current food systems at scale requires a dynamic science-policy- society interface, global-spanning networks, and knowledge brokering nodes to promote learning, reflection, dialog, and address power struggles at and across local and global scales (Singh et al., 2023). These authors call for strengthening multilateral institutions and creating global coordination and task forces for a global "network of networks" with a clear mandate to engage across food sectors and scales. This may require significant political will and convergence among global private and public food system actors to mobilize the institutional and financial resources needed for such large-scale investments.

Thus, while food system governance scholars may propose possible ways forward and provide normative guidance or aspirational perspectives (e.g., on how food system integration could happen; Edwards et al., 2024), the nature of the real-world challenges demands a different approach. More specifically, rather than a management problem with a clear beginning and end, governing food system transformation demands a continuous and long-term process accompanied by an in-depth understanding of food system dynamics, the presence of pluralistic understandings of causality ('as a web of interlocking factors'; Middlemiss, 2018, p. 207) and the values and power positions of the different stakeholders involved. Learning becomes a key activity to invest in, along with flexibility (Termeer et al., 2015) and reflexivity (Grin, 2006; Neufeldt et al., 2013). Being a deeply political process (Gillespie et al., 2019a; Meadowcroft, 2007; Scoones et al., 2020; Swinburn, 2019), promoting a shared and inclusive vision for the transformation of food systems will require engaging and making the most of power struggles (Caron et al., 2018). This may already be happening as a growing number of NGOs are taking on new roles in food democracy through participation in multi-stakeholder platforms (MSPs) aiming at transforming food systems (Van Den Akker et al., 2024). However, as found by these authors, private sectors still hold central positions of power in these MSP networks, while NGOs are still largely underrepresented at only 10 and 4% of the 813 MSP actors mapped in high-income and low-income countries, respectively. In order to address the food system governance challenges discussed above, a recent review of alternatives found in the literature on food system transformation (Kraak and Niewolny, 2024) suggests that efforts may be needed to support a variety of strategies to drive social and political change and promote the participation and inclusion of civil society actors with different food system visions, narratives and values in transparent deliberative decision-making processes and the engagement of global to local food system networks. Examples of possible alternatives mentioned in this review include political consumerism that embraces market-driven processes, building alliances across diverse constituencies, electoral advocacy activities, and collective protest politics to influence public policy- making spaces.

Author contributions

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References

Achrol, R. S. (1996). Changes in the theory of interorganizational relations in marketing: toward a network paradigm. *J. Acad. Mark. Sci.* 25, 56–71. doi: 10.1177/0092070397251006

Anderson, C. R., Bruil, J., Chappell, M. J., Kiss, C., and Pimbert, M. P. (2019). From transition to domains of transformation: getting to sustainable and just food systems through agroecology. *Sustain. For.* 11:5272. doi: 10.3390/su11195272

Ansell, C., and Gash, A. (2007). Collaborative governance in theory and practice. *J. Public Adm. Res. Theory* 18, 543–571. doi: 10.1093/jopart/mum032

Béné, C. (2005). The good, the bad and the ugly: discourse, policy controversies, and the role of science in the politics of shrimp farming development. *Dev. Policy Rev.* 23, 585–614. doi: 10.1111/j.1467-7679.2005.00304.x

Béné, C., and Abdulai, A. R. (2024). Navigating the politics and processes of food systems transformation: guidance from a holistic framework. *Front. Sustain. Food Syst.* 8:1399024. doi: 10.3389/fsufs.2024.1399024

Béné, C., Oosterveer, P., Lamotte, L., Brouwer, I. D., de Haan, S., Prager, S. D., et al. (2019). When food systems meet sustainability – current narratives and implications for actions. *World Dev.* 113, 116–130. doi: 10.1016/j.worlddev.2018.08.011

Bertalanffy, L. V. (1972). The history and status of general systems theory. *Acad. Manag. J.* 15, 407–426. doi: 10.5465/255139

Bouwma, I., Schleyer, C., Primmer, E., Winkler, K. J., Berry, P., Young, J., et al. (2018). Adoption of the ecosystem services concept in EU policies. *Ecosyst. Serv.* 29, 213–222. doi: 10.1016/j.ecoser.2017.02.014

Bush, R. (2010). Food Riots: Poverty, Power and Protest1. *J. Agrarian Change* 10, 119–129. doi: 10.1111/j.1471-0366.2009.00253.x

Burch, D., and Lawrence, G. (2005). Supermarket own brands, supply chains and the transformation of the Agri-food system. *Int. J. Sociol. Agric. Food* 13, 1–18.

Burgers, P., and Susanti, A. (2011). *The focus: food security and land grabbing; a new equation for oil palm & food, energy and climate policies in Riau Province, Indonesia*. IIAS the newsletter, 58 (autumn/winter 2011), 22–23.

Candel, J. J. L. (2014). Food security governance: a systematic literature review. *Food Secur.* 6, 585–601. doi: 10.1007/s12571-014-0364-2

Caron, P., Ferrero de Loma-Osorio, G., Nabarro, D., Hainzelin, E., Guillou, M., Andersen, I., et al. (2018). Food systems for sustainable development: proposals for a profound four-part transformation. *Agron. Sustain. Dev.* 38:41. doi: 10.1007/s13593-018-0519-1

Castells, M. (2009). Communication power. Oxford: Oxford University Press.

Centner, T. J., and Heric, D. C. (2019). Anti-community state pesticide preemption laws prevent local governments from protecting people from harm. *Int. J. Agric. Sustain.* 17, 118–126. doi: 10.1080/14735903.2019.1568814

Clapp, J. (2003). Transnational corporate interests and global environmental governance: negotiating rules for agricultural biotechnology and chemicals. *Environ. Polit.* 12, 1–23. doi: 10.1080/09644010412331308354

Clapp, J. (2014). Financialization, distance and global food politics. *J. Peasant Stud.* 41, 797–814. doi: 10.1080/03066150.2013.875536

Clapp, J. (2017). "Financialization, distance and global food politics" in New directions in agrarian political economy (London: Routledge), 157–174.

Clapp, J. (2021). The problem with growing corporate concentration and power in the global food system. *Nature Food* 2, 404–408. doi: 10.1038/s43016-021-00297-7

Clapp, J., and Isakson, S. R. (2018). Risky returns: the implications of financialization in the food system. *Dev. Chang.* 49, 437–460. doi: 10.1111/dech.12376

De Brauw, A., Brouwer, I. D., Snoek, H., Vignola, R., Melesse, M. B., Lochetti, G., et al. (2019). Food system innovations for healthier diets in low and middle-income countries. IFPRI discussion paper, vol. *1816*. Washington, DC: International food Policy Research Institute.

de Krom, M. P., and Muilwijk, H. (2019). Multiplicity of perspectives on sustainable food: moving beyond discursive path dependency in food policy. *Sustain. For.* 11:2773. doi: 10.3390/su11102773

De Schutter, O. (2017). The political economy of food systems reform. *Eur. Rev. Agric. Econ.* 44, 705–731. doi: 10.1093/erae/jbx009

Delaney, A., Evans, T., McGreevy, J., Blekking, J., Schlachter, T., Korhonen-Kurki, K., et al. (2018). Governance of food systems across scales in times of social-ecological change: a review of indicators. *Food Secur.* 10, 287–310. doi: 10.1007/s12571-018-0770-y

den Boer, A. C., van der Valk, A. J., Regeer, B. J., and Broerse, J. E. (2023). Food policy networks and their potential to stimulate systemic intermediation for food system transformation. *Cities* 135:104239. doi: 10.1016/j.cities.2023.104239

Dicken, P., Kelly, P. F., Olds, K., and Wai-Chung Yeung, H. (2001). Chains and networks, territories and scales: towards a relational framework for analysing the global economy. *Global Netw.* 1, 89–112. doi: 10.1111/1471-0374.00007

D'Odorico, P., Davis, K. F., Rosa, L., Carr, J. A., Chiarelli, D., Dell'Angelo, J., et al. (2018). The global food-energy-water nexus. *Rev. Geophys.* 56, 456–531. doi: 10.1029/2017RG000591

Ducastel, A., and Anseeuw, W. (2013). Agriculture as an asset class: Financialisation of the South African farming sector. Rural transformations and food systems: The BRICS and agrarian change in the global South' conference, Cape Town.

Durant, R. F., Chun, Y. P., Kim, B., and Lee, S. (2004). Toward a new governance paradigm for environmental and natural resources management in the 21st century? *Adm. Society* 35, 643–682. doi: 10.1177/0095399703256968

Edwards, F., Sonnino, R., and Cifuentes, M. L. (2024). Connecting the dots: integrating food policies towards food system transformation. *Environ. Sci. Pol.* 156:103735. doi: 10.1016/j.envsci.2024.103735

El Bilali, H. (2019). Research on agro-food sustainability transitions: a systematic review of research themes and an analysis of research gaps. *J. Clean. Prod.* 221, 353–364. doi: 10.1016/j.jclepro.2019.02.232

Erixon, F., and Lamprecht, P. (2020). The role of trade policy in promoting sustainable agriculture. Brussels: European Centre for International Political Economy.

Fanzo, J., Hunter, D., Borelli, T., and Mattei, F. (Eds.) (2013). Diversifying food and diets. London: Routledge.

FAO, IFAD, UNICEF, WFP, and WHO. (2018). The state of food security and nutrition in the world 2018. Building climate resilience for food security and nutrition. Available online at: http://www.fao.org/3/I9553EN/i9553en.pdf (Accessed January 30, 2019)

Farsund, A. A., Daugbjerg, C., and Langhelle, O. (2015). Food security and trade: reconciling discourses in the food and agriculture organization and the World Trade Organization. *Food Secur.* 7, 383–391. doi: 10.1007/s12571-015-0428-y

Frederick, S., Loewenstein, G., and O'donoghue, T. (2002). Time discounting and time preference: a critical review. *J. Econ. Lit.* 40, 351–401. doi: 10.1257/jel.40.2.351

Gaitán-Cremaschi, D., Klerkx, L., Duncan, J., Trienekens, J. H., Huenchuleo, C., Dogliotti, S., et al. (2018). Characterizing diversity of food systems in view of sustainability transitions. A review. *Agron. Sustain. Dev.* 39:1. doi: 10.1007/s13593-018-0550-2

Galaz, V., Crona, B., Dauriach, A., Jouffray, J. B., Österblom, H., and Fichtner, J. (2018). Tax havens and global environmental degradation. *Nature Ecol. Evol.* 2, 1352–1357. doi: 10.1038/s41559-018-0497-3

Galluzzi, G., Eyzaguirre, P., and Negri, V. (2010). Home gardens: neglected hotspots of agro-biodiversity and cultural diversity. *Biodivers. Conserv.* 19, 3635–3654. doi: 10.1007/s10531-010-9919-5

Geels, F. W. (2011). The multi-level perspective on sustainability transitions: responses to seven criticisms. *Environ. Innov. Soc. Trans.* 1, 24–40. doi: 10.1016/j.eist.2011.02.002

Geels, F. W. (2014). Regime resistance against low-carbon transitions: introducing politics and power into the multi-level perspective. *Theory Cult. Soc.* 31, 21–40. doi: 10.1177/0263276414531627

Geels, F. W., and Schot, J. (2007). Typology of sociotechnical transition pathways. *Res. Policy* 36, 399–417. doi: 10.1016/j.respol.2007.01.003

Gillespie, S., Poole, N., van den Bold, M., Bhavani, R. V., Dangour, A. D., and Shetty, P. (2019a). Leveraging agriculture for nutrition in South Asia: what do we know, and what have we learned? *Food Policy* 82, 3–12. doi: 10.1016/j.foodpol.2018.10.012

Gillespie, S., van den Bold, M., and Hodge, J. (2019b). Nutrition and the governance of Agri-food systems in South Asia: a systematic review. *Food Policy* 82, 13–27. doi: 10.1016/j.foodpol.2018.10.013

Gliessman, S. (2013). Agroecology: growing the roots of resistance. *Agroecol. Sustain. Food Syst.* 37, 507–508. doi: 10.1080/21683565.2013.764957

Grin, J. (2006). "Reflexive modernisation as a governance issue, or: designing and shaping *re*-structuration" in Reflexive governance for sustainable development. eds. J.-P. Voss, D. Bauknecht and R. Kemp (Cheltenham and Northampton: Edward Elgar), 57–81.

Guthman, J. (2007). The Polanyian way? Voluntary food labels as neoliberal governance. *Antipode* 39, 456–478. doi: 10.1111/j.1467-8330.2007.00535.x

Haddad, L. (2023). Essential steps for transforming national food systems. *Nature Food* 4, 630–631.

Hall, R. (2011). Land grabbing in southern Africa: the many faces of the investor rush [review of African political economy]. *Rev. Afr. Polit. Econ.* 38, 193–214. doi: 10.1080/03056244.2011.582753

Hauck, J., Schmidt, J., and Werner, A. (2016). Using social network analysis to identify key stakeholders in agricultural biodiversity governance and related land-use decisions at regional and local level. *Ecol. Soc.* 21. doi: 10.5751/ES-08596-210249

Herring, R. J. (2015a). "How is food political? Market, state and knowledge" in The Oxford handbook of food, politics, and society. ed. R. J. Herring (Oxford: Oxford University Press), 3–40.

Herring, R. J. (Ed.) (2015b). The Oxford handbook of food, politics, and society. Oxford: Oxford University Press.

High Level Panel of Experts on Food and Nutrition (HLPE) (2017). "Nutrition and food systems" in A report of the high level panel of experts on food security and nutrition of the committee on world food security (Rome: HLPE).

Hooghe, L., and Marks, G. (2003). Unraveling the central state, but how? Types of multi-level governance. *Am. Polit. Sci. Rev.* 97, 233–243. doi: 10.1017/s0003055403000649

Hoppe, R., and Turnbull, N. (2023). Problem structuring, wrong-problem problems and metagovernance as the strategic management of intractable positions: the case of the EU GM crop regulatory framework controversy. *Public Policy Adm.* 39, 475–496. doi: 10.1177/09520767231177577

Hornberger, G. M., and Spear, R. C. (1981). An approach to the preliminary analysis of environmental systems. *J. Environ. Manag.* 12, 7–18.

Hospes, O., and Brons, A. (2016). "Food system governance. A systematic literature review" in Food systems governance. Challenges for justice, equality and human rights. eds. A. Kennedy and J. Liljeblad (London: Routledge), 13–42.

IPBES (2022). "Summary for policymakers of the methodological assessment report on the diverse values and valuation of nature of the intergovernmental science-policy platform on biodiversity and ecosystem services" in IPBES secretariat. eds. U. Pascual, P. Balvanera, M. Christie, B. Baptiste, D. González-Jiménez and C. B. Anderson (Bonn: IPBES).

IPES-Food (2023). Who's tipping the scales? The growing influence of corporations on the governance of food systems, and how to counter it. *IPES-Food*.

Jessop, B. (2003). "Governance and meta-governance: on reflexivity, requisite variety and requisite irony" in Governance as social and political communication. ed. H. P. Bang, 101–116.

Jones, C., Hesterly, W. S., and Borgatti, S. P. (1997). A general theory of network governance: exchange conditions and social mechanisms. *Acad. Manag. Rev.* 22, 911–945. doi: 10.5465/amr.1997.9711022109

Jordan, A., and Lenschow, A. (2010). Environmental policy integration: a state of the art review. *Environ. Policy Gov.* 20, 147–158. doi: 10.1002/eet.539

Juri, S., Terry, N., and Pereira, L. M. (2024). Demystifying food systems transformation: a review of the state of the field. *Ecol. Soc.* 29. doi: 10.5751/ES-14525-290205

Kay, A. (2005). A Critique of the Use of Path Dependency in Policy Studies. *Public Administration* 83, 553–571. doi: 10.1111/j.0033-3298.2005.00462.x

Keleman, A., Hellin, J., and Bellon, M. R. (2009). Maize diversity, rural development policy, and farmers' practices: lessons from Chiapas, Mexico. *Geograph. J.* 175, 52–70. doi: 10.1111/j.1475-4959.2008.00314.x

Kooiman, J., Bavinck, M., Chuenpagdee, R., Mahon, R., and Pullin, R. (2008). Interactive governance and governability: an introduction. *J. Transdiscipl. Environ. Stud.* 7, 1–11.

Kooiman, J., and Jentoft, S. (2009). Meta-governance: values, norms and principles, and the making of hard choices. *Public Adm.* 87, 818–836. doi: 10.1111/j.1467-9299.2009.01780.x

Kraak, V. I., and Niewolny, K. L. (2024). A scoping review of food systems governance frameworks and models to develop a typology for social change movements to transform food systems for people and planetary health. *Sustain. For.* 16:1469. doi: 10.3390/su16041469

Kuokkanen, A., Mikkilä, M., Kuisma, M., Kahiluoto, H., and Linnanen, L. (2017). The need for policy to address the food system lock-in: A case study of the Finnish context. *J. Cleaner Production* 140, 933–944. doi: 10.1016/j.jclepro.2016.06.171

Leach, M., Nisbett, N., Cabral, L., Harris, J., Hossain, N., and Thompson, J. (2020). Food politics and development. *World Dev.* 134:105024. doi: 10.1016/j.worlddev.2020.105024

Loorbach, D., Frantzeskaki, N., and Avelino, F. (2017). Sustainability transitions Research: transforming science and practice for societal change. *Annu. Rev. Environ. Resour.* 42, 599–626. doi: 10.1146/annurev-environ-102014-021340

Mac Donald, G. K., Brauman, K. A., Sun, S., Carlson, K. M., Cassidy, E. S., Gerber, J. S., et al. (2015). Rethinking agricultural trade relationships in an era of globalization. *Bio Sci.* 65, 275–289.

Margulis, M. E. (2014). Trading out of the global food crisis? The World Trade Organization and the geopolitics of food security. *Geopolitics* 19, 322–350. doi: 10.1080/14650045.2014.920233

Margulis, M. E., McKeon, N., and Borras, S. M. (2013). Land grabbing and global governance: critical perspectives. *Globalizations* 10, 1–23. doi: 10.1080/14747731.2013.764151

Marks-Bielska, R., and Babuchowska, K. (2010). Functioning of the direct subsidies system in Poland and other European Union countries. *J. Agribusiness Rural Dev.* 17, 89–100.

Mayer, C. (1990). "Financial systems, corporate finance, and economic development" in Asymmetric information, corporate finance, and investment. ed. National Bureau of Economic Research (Chicago: University of Chicago Press), 307–332.

Meadowcroft, J. (2007). Who is in charge here? Governance for sustainable development in a complex world*. *J. Environ. Policy Plann.* 9, 299–314. doi: 10.1080/15239080701631544

Meadows, D. (1999). Leverage points: Places to intervene in a system. Available online at: Hartland.

Middlemiss, L. (2018). "Sustainable consumption. Key issues" in Series: Key issues in environment and sustainability (Abingdon, Oxon: Routledge).

Mol, A. P. J. (2010). "Social theories of environmental reform: towards a third generation" in Environmental Sociology. eds. M. Gross and H. Heinrichs (Dordrecht: Springer), 19–38.

Murdoch, J., Marsden, T., and Banks, J. (2000). Quality, nature, and embeddedness: some theoretical considerations in the context of the food sector. *Econ. Geogr.* 76, 107–125.

Neufeldt, H., Jahn, M., Campbell, B. M., Beddington, J. R., DeClerck, F., De Pinto, A., et al. (2013). Beyond climate-smart agriculture: toward safe operating spaces for global food systems. *Agric. Food Secur.* 2:12. doi: 10.1186/2048-7010-2-12

Nguyen, H., Morrison, J., and Neven, D. (2019). "Changing food systems: implications for food security and nutrition" in Chapter 9 in sustainable food and agriculture (Cambridge, MA: Academic Press), 153–168.

Oñederra-Aramendi, A., Begiristain-Zubillaga, M., and Cuellar-Padilla, M. (2023). Characterisation of food governance for alternative and sustainable food systems: a systematic review. *Agric. Food Econ.* 11:18. doi: 10.1186/s40100-023-00258-7

Oosterveer, P., (2006). Environmental governance of global food flows: the case of labeling strategies. In G. Spaargaren, , , A.P.J. Mol, and , and F.H Buttel, . (Eds.). Governing environmental flows: Global challenges to social theory. Cambridge: MIT Press.

Oosterveer, P. (2007). Global governance of food production and consumption. Issues and challenges. Cheltenham: Edward Elgar Publishing.

Oosterveer, P. (2015a). Promoting sustainable palm oil: viewed from a global networks and flows perspective. *J. Clean. Prod.* 107, 146–153. doi: 10.1016/j.jclepro.2014.01.019

Oosterveer, P. (2015b). Sustainable food governance by governments and markets: the case of sustainable seafood provision. *European J. Risk Regul.* 6, 525–531. doi: 10.1017/S1867299X00005080

Osiemo, O. (2024). A bridge too far: Africa's food security and the WTO agreement on agriculture. *African J. Int. Comparat. Law* 32, 478–502. doi: 10.3366/ajicl.2024.0501

Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science* 325, 419–422. doi: 10.1126/science.1172133

Pahl-Wostl, C., Gorris, P., Jager, N., Koch, L., Lebel, L., Stein, C., et al. (2021). Scale-related governance challenges in the water–energy–food nexus: toward a diagnostic approach. *Sustain. Sci.* 16, 615–629. doi: 10.1007/s11625-020-00888-6

Parker, C., and Johnson, H. (2019). From Food Chains to Food Webs: Regulating Capitalist Production and Consumption in the Food System. *Annual Review of Law and Social Science* 15, 205–225. doi: 10.1146/annurev-lawsocsci-101518-042908

Parsons, K., and Hawkes, C. (2018). Connecting food systems for co-benefits: How can food systems combine diet-related health with environmental and economic policy goals? Available online at: Copenhagen.

Piattoni, S. (2009). Multi-level governance: a historical and conceptual analysis. *European Integration* 31, 163–180. doi: 10.1080/07036330802642755

Piñeiro, V., Arias, J., Dürr, J., Elverdin, P., Ibáñez, A. M., Kinengyere, A., et al. (2020). A scoping review on incentives for adoption of sustainable agricultural practices and their outcomes. *Nature Sustain.* 3, 809–820. doi: 10.1038/s41893-020-00617-y

Porkka, M., Kummu, M., Siebert, S., and Varis, O. (2013). From food insufficiency towards trade dependency: a historical analysis of global food availability. *PloS One* 8:e82714. doi: 10.1371/journal.pone.0082714

Provan, K. G., and Kenis, P. (2008). Modes of network governance: structure, management, and effectiveness. *J. Public Adm. Res. Theory* 18, 229–252. doi: 10.1093/jopart/mum015

Rapoport, A. (1986). General system theory. Essential Concepts & Applications. Turnbridge Wells: Abacus Press.

Reardon, T., and Hopkins, R. (2006). The supermarket revolution in developing countries: policies to address emerging tensions among supermarkets, suppliers and traditional retailers. *Eur. J. Dev. Res.* 18, 522–545. doi: 10.1080/09578810601070613

Reh, C. (2012). Informal politics: The normative challenge. International handbook on informal governance, Cheltenham: Edward Elgar Publishing.

Resnick, D., and Swinnen, J. (2023). The political economy of food system transformation: Pathways to Progress in a polarized world. Oxford: Oxford University Press, 1.

Rockström, J., Edenhofer, O., Gaertner, J., and DeClerck, F. (2020). Planet-proofing the global food system. *Nature Food* 1, 3–5. doi: 10.1038/s43016-019-0010-4

Ruben, R., Verhagen, J., and Plaisier, C. (2018). The challenge of food systems research: what difference does it make? *Towards Sustain. Global Food Syst.* 11. doi: 10.3390/su11010171

Rudnick, J., Niles, M., Lubell, M., and Cramer, L. (2019). A comparative analysis of governance and leadership in agricultural development policy networks. *World Dev.* 117, 112–126. doi: 10.1016/j.worlddev.2018.12.015

Ruggeri, K., Panin, A., Vdovic, M., Većkalov, B., Abdul-Salaam, N., Achterberg, J., et al. (2022). The globalizability of temporal discounting. *Nat. Hum. Behav.* 6, 1386–1397. doi: 10.1038/s41562-022-01392-w

Sahota, A. (2009). "The global market for organic food & drink" in The world of organic agriculture, Statistics and Emerging Trends. eds. H. Willer and L. Kilcher, vol. *2009* (Bonn: FIBL-IFOAM Report).

Samerwong, P., Bush, S. R., and Oosterveer, P. (2017). Metagoverning aquaculture standards: a comparison of the GSSI, the ASEAN GAP, and the ISEAL. *J. Environ. Dev.* 26, 429–451. doi: 10.1177/1070496517736872

Scoones, I., Stirling, A., Abrol, D., Atela, J., Charli-Joseph, L., Eakin, H., et al. (2020). Transformations to sustainability: combining structural, systemic and enabling approaches. *Curr. Opin. Environ. Sustain.* 42, 65–75. doi: 10.1016/j.cosust.2019.12.004

Singh, B. K., Fraser, E. D., Arnold, T., Biermayr-Jenzano, P., Broerse, J. E., Brunori, G., et al. (2023). Food systems transformation requires science–policy–society interfaces that integrate existing global networks and new knowledge hubs. *Nature food* 4, 1–3. doi: 10.1038/s43016-022-00664-y

Smith, P., House, J. I., Bustamante, M., Sobocká, J., Harper, R., Pan, G., et al. (2016). Global change pressures on soils from land use and management. *Glob. Chang. Biol.* 22, 1008–1028. doi: 10.1111/gcb.13068

Spaargaren, G., Oosterveer, P., and Loeber, A. (2012). Food practices in transition. Changing food consumption, retail and production in the age of reflexive modernity. London: Routledge.

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B. L., Lassaletta, L., et al. (2018). Options for keeping the food system within environmental limits. *Nature* 562, 519–525. doi: 10.1038/s41586-018-0594-0

Stoker, G. (1998). Governance as theory: five propositions. *Int. Soc. Sci. J.* 50, 17–28. doi: 10.1111/1468-2451.00106

Swinburn, B. (2019). Power dynamics in 21st-century food systems. *Nutrients* 11:2544. doi: 10.3390/nu11102544

Swinburn, B. A., Kraak, V. I., Allender, S., Atkins, V. J., Baker, P. I., Bogard, J. R., et al. (2019). The global syndemic of obesity, undernutrition, and climate change: the lancet commission report. *Lancet* 393, 791–846. doi: 10.1016/S0140-6736(18)32822-8

Termeer, C. J., Dewulf, A., and Biesbroek, G. R. (2017). Transformational change: governance interventions for climate change adaptation from a continuous change perspective. *J. Environ. Plan. Manag.* 60, 558–576. doi: 10.1080/09640568.2016.1168288

Termeer, C. J. A. M., Dewulf, A., Breeman, G., and Stiller, S. J. (2015). Governance capabilities for dealing wisely with wicked problems. *Adm. Soc.* 47, 680–710. doi: 10.1177/0095399712469195

Termeer, C. J. A. M., Drimie, S., Ingram, J., Pereira, L., and Whittingham, M. J. (2018). A diagnostic framework for food system governance arrangements: the case of South Africa. *NJAS* 84, 85–93. doi: 10.1016/j.njas.2017.08.001

Thompson, J., and Scoones, I. (2009). Addressing the dynamics of Agri-food systems: an emerging agenda for social science research [special issue: food security and environmental change food security and environmental change: linking science, development and policy for adaptation]. *Environ. Sci. Policy* 12, 386–397. doi: 10.1016/j.envsci.2009.03.001

Urzedo, D. I., Neilson, J., Fisher, R., and Junqueira, R. G. (2020). A global production network for ecosystem services: The emergent governance of landscape restoration in the Brazilian Amazon. *Glob. Environ. Change* 61:102059.

van Bers, C., Delaney, A., Eakin, H., Cramer, L., Purdon, M., Oberlack, C., et al. (2019). Advancing the research agenda on food systems governance and transformation. *Curr. Opin. Environ. Sustain.* 39, 94–102. doi: 10.1016/j.cosust.2019.08.003

Van Bers, C. V., Pahl-Wostl, C., Eakin, H., Ericksen, P. J., Lenaerts, L., Förch, W., et al. (2016). Transformation in governance towards resilient food systems. CCAFS working paper no. 190. Copenhagen, Denmark: CGIAR Research program on climate change, agriculture and food security (CCAFS).

Van Den Akker, A., Fabbri, A., Slater, S., Gilmore, A. B., Knai, C., and Rutter, H. (2024). Mapping actor networks in global multi-stakeholder initiatives for food system transformation. *Food Secur.* 16, 1223–1234. doi: 10.1007/s12571-024-01476-7

Vignola, R., Harvey, C. A., Bautista-Solis, P., Avelino, J., Rapidel, B., Donatti, C., et al. (2015). Ecosystem-based adaptation for smallholder farmers: definitions, opportunities and constraints. *Agri. Ecosyst. Environ.* 211, 126–132.

Visseren-Hamakers, I. J., Razzaque, J., McElwee, P., Turnhout, E., Kelemen, E., Rusch, G. M., et al. (2021). Transformative governance of biodiversity: insights for sustainable development. *Curr. Opin. Environ. Sustain.* 53, 20–28. doi: 10.1016/j.cosust.2021.06.002

Wang, H., and Ran, B. (2023). Network governance and collaborative governance: a thematic analysis on their similarities, differences, and entanglements. *Public Manag. Rev.* 25, 1187–1211. doi: 10.1080/14719037.2021.2011389

Weber, H., Poeggel, K., Eakin, H., Fischer, D., Lang, D. J., Wehrden, H. V., et al. (2020). What are the ingredients for food systems change towards sustainability?—insights from the literature. *Environ. Res. Lett.* 15:113001. doi: 10.1088/1748-9326/ab99fd

Wilkinson, G., and Dale, B. G. (1999). Integrated management systems: an examination of the concept and theory. *TQM Mag.* 11, 95–104. doi: 10.1108/09544789910257280

Yeoman, R., and Santos, M. M. (2019). "Global value chains, reputation, and social cooperation" in Global aspects of reputation and strategic management (Bingley: Emerald Publishing Limited), 69–91.

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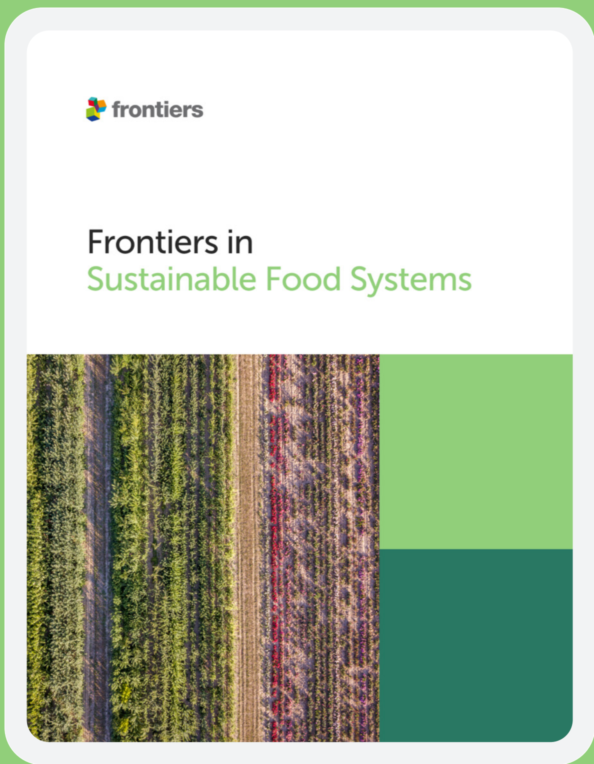

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