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Impacts of climate change on tropical agroforestry systems: A systematic review for identifying future research priorities

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Climate change is expected to adversely affect the crop yields and food security for many smallholder farmers in the tropics unless adaptive measures are implemented. Agroforestry ecosystem services, such as micro-climate buffering, have received growing attention from the academic and policy communities for alleviating the negative impacts of climate change on smallholders. These benefits imply that agroforestry could offer a suitable measure for adaptation to climate change. However, whether agroforestry systems themselves succumb to the adverse effects of climate change is often less studied in the agroforestry literature. Consequently, less is known about how climate change will impact agroforests. We conducted a systematic review, which included an evidence quality assessment, to examine the impacts of climate change on tropical agroforestry systems (TAFS). Based primarily on studies undertaking biophysical approaches, we found that climate change negatively impacts TAFS by reducing tree growth, intensifying tree-crop resource competition and reducing crop yields. However, the impacts on smallholder farmers are less clear due to limited evidence in the relevant literature. We found that the evidence supporting our findings is mostly "robust", although "least robust" strength evidence was also commonly found. We conclude that to improve understanding of how climate change could affect the performance of TAFS as a social ecological system, more interdisciplinary studies are required. Furthermore, to improve the quality of evidence in the research field, studies should explore using mountain elevation gradients for climate analog analysis to perform the most robust study designs. We provide an interdisciplinary conceptual model, which considers the interactions and feedbacks between TAFS components noted from our review to predict the response of ecosystem services provisioning and farmers' wellbeing to climate change, to guide interdisciplinary studies using climate analog analysis.

KEYWORDS

ecosystem services (ES), climate resilience, drought, global warming, homegardens

Introduction

Agroforestry, termed tropical agroforestry systems (TAFS) in the tropics, involves the integration of trees into farmland for socio-economic and ecological benefits (Schroth et al., 2004). Using a broad definition of trees in agricultural land, TAFS cover around 12.3 million km² of global farmland (approximately 25% of total agricultural land) with high coverage in Southeast Asia, Central America, eastern South America and central and coastal West Africa (Zomer et al., 2016). TAFS usually display greater animal and plant species per unit area and more canopy layers than other agroforestry systems (Pathak and Dagar, 2000). The types of agroforestry systems are defined by their structure (i.e., arrangement of components), function (i.e., acting as windbreaks), socio-economic purpose (i.e., commercial or subsistence), and ecological characteristics (i.e., ecological conditions that influence which agroforestry systems can be practiced) which pertain to the environment of a geographic region (Nair, 1993; Dagar and Tewari, 2017). The main types of TAFS include multipurpose trees on woodlots (community forests providing forest products) and cropland, taungya systems (short-term crops cultivated with cleared and re-planted forest) and homegardens (intermixing and layering of trees with plants and crops at different vertical canopy strata) (Table 1). Homegardens, are particularly diverse systems, usually exhibiting the richest biodiversity per unit area of all agroforests (Dagar and Tewari, 2017). The biotic features of a TAFS are influenced mainly by their environmental ecological and agroclimatic conditions (Atangana et al., 2014). For example, TAFS found in the humid highland tropics exhibit higher species richness than those in highland semiarid tropics due to differences in temperature and rainfall (Dagar and Tewari, 2017).

TAFS are important for the wellbeing of rural communities. These systems provide people with crops, fruits, and products which can be exchanged amongst communities to establish and reinforce social relationships (Blanckaert et al., 2004; Maroyi, 2009; Hashini Galhena et al., 2013). Such systems supporting indigenous crops and plants also support people's cultural values (Blanckaert et al., 2004; Linger, 2014). Homegardens, for example, enable people to manage traditional crops and plants belonging to their cultural history (Blanckaert et al., 2004), whilst coffee produced in TAFS allows people to partake in important religious coffee-related ceremonies within their communities (Linger, 2014). Regarding health and nutrition, TAFS provide diverse livestock products, fruit, and vegetable crops high in dietary micronutrients, calories, and protein (Talukder et al., 2000; de la Cerda and Mukul, 2008; Whitney et al., 2018). Other products, such as medicinal plants, treat diseases and illnesses (Hashini Galhena et al., 2013; Landreth and Saito, 2014). Returns for TAFS crops can be higher than open-field crops (Marsh, 1998) and provide income for even the poorest households (Mitchell and Hanstad, 2004; Hashini

Galhena et al., 2013). In Sub-Saharan Africa, for example, TAFS crops can account for over 60% of household income (Okigbo, 1990). Such income enables households to improve their living standards, such as housing and cooking fuel (Kumar and Nair, 2004), and access education (Vasey, 1985; Iannotti et al., 2009; Maroyi, 2009). Concerning people's freedom of choice, crop production in TAFS can enhance farmers' self-sufficiency (Kumar and Nair, 2004), whilst women's involvement in farming and selling TAFS products generates personal income benefitting their independence (Marsh, 1998).

In the tropics, climate change will create warmer and drier environments, increasingly variable rainfall regimes and more frequent climate extremes (Serdeczny et al., 2017; Siyum, 2020). In contrast to cooler global regions, rises in temperature are expected to be stronger in the tropics (Gasparrini et al., 2017). Just a 2°C temperature increase risks substantial decreases in some crop yields grown by the 396 million of the approximately 900 million people involved in agriculture, which would severely impact livelihoods, food security and wellbeing unless adaptive measures are implemented (Zomer et al., 2016; Roy et al., 2018). Consequently, agroforestry has received growing interest as an adaptation to climate change measure for smallholder farmers (Palm et al., 2010; Lasco et al., 2014; Campbell et al., 2016; Ram et al., 2016; Altieri and Nicholls, 2017; Waldron et al., 2017). Most low-income countries (63 out of 88) now mention agroforestry as an adaptation solution in their climate change inventories, with the most interest in the tropics (Rosenstock et al., 2018).

Proponents contend that TAFS increase farmers' climate resilience through their regulating ecosystem services (Verchot et al., 2007; ICRAF, 2008; Thangata and Hildebrand, 2012; Nguyen et al., 2013; Garedew et al., 2017; Vargas Zeppetello et al., 2022). Tree canopies can lower irradiance and ambient air and soil temperature through shading effects (Mohri et al., 2013; van Noordwijk et al., 2021). Tree shading can lower ambient temperatures by 4°C (Liu et al., 2019) and soil temperatures by 6–10°C (Vandenbeldt and Williams, 1992; Belsky et al., 1993). More recent research shows that in tropical silvopastoral systems cooling effects are positively associated with increased woody carbon density (Vargas Zeppetello et al., 2022). TAFS can thereby regulate humidity, soil moisture evaporation and plant evapotranspiration (Lin et al., 2008) and, in turn, reduce water losses from crops and sustain production during heat stress (Rahn et al., 2018; Sida et al., 2018). Tree roots also aid soil water infiltration, reduce surface runoff, and reduce soil erosion during rainfall (Vaast et al., 2008; Siles et al., 2010). Tree biomass transfer increases soil organic matter, which improves soil aggregation stability, water retention capacity and infiltration preserving soil moisture (Phiri et al., 2003; Sileshi and Mafongoya, 2006; Wu et al., 2016). Tree canopies can also intercept precipitation and reduce throughfall (Dietz et al., 2006; Ilstedt et al., 2016), which mitigates soil erosion and crop damage caused by heavy rainfalls (Thorlakson and Neufeldt, 2012).

TABLE 1 Spread of the main types of tropical agroforestry systems based on supporting ecological conditions.

	Elevation (m asl)	Sub-humid to perarid	Semi-humid to semiarid	Pre-humid to sub-humid
		Annual rainfall (mm) <500	Annual rainfall (mm) 500–1200	Annual rainfall (mm) >1200
Lowlands	<500	Homegardens	Improved fallows	Homegardens
		Multipurpose woodlots	Trees on pasturelands	Improved fallows
		Multipurpose trees on cropland	Multipurpose trees woodlots	Trees in pisciculture
		Trees on pasturelands	Homegardens	Alley cropping
			Plantation crop combinations	Taungya
			Alley cropping	Multipurpose trees woodlots
			Tree hedgerows	Plantation crop combinations
			Taungya	Multipurpose trees on cropland
Midland	500–1,200	Multipurpose trees on woodlots	Plantation crop combinations	Alley Cropping
		Tree hedgerows	Trees on pasturelands	Improved fallows
		Multipurpose trees on cropland	Improved fallows	Homegardens
		Trees on pasturelands	Taungya	Plantation crop combinations
			Multipurpose trees woodlots	Multipurpose trees on croplands
			Multipurpose trees on croplands	Taungya
			Homegardens	Multipurpose trees woodlots
		Plantation crop combinations	Trees on pasturelands	
Highlands	>1,200	Trees on pasturelands	Taungya	Homegardens
			Multipurpose trees woodlots	Taungya
			Multipurpose trees on croplands	Multipurpose trees on croplands
			Trees on pasturelands	Tree hedgerows

Foliated trees can reduce rainwater reaching crops by 10–50% (Rao et al., 1998), and in homegardens rainwater interception can reach 54% (Otte et al., 2017).

Provisioning ecosystem services from agroforests can also increase smallholder farmers' climate resilience through the provision of crops and other products directly to households (Sileshi et al., 2007; Quandt et al., 2018). The replenishment of soil nutrients by TAFS can permit the sustainable cultivation of various crops (Neupane et al., 2002; Jose, 2009; Ajayi et al., 2011) grown year-round under agroforestry's micro-climate effects (Charles et al., 2014). By supplying high diversities of crops and products (Abebe et al., 2006; Hashini Galhena et al., 2013; Jemal et al., 2018) TAFS can alleviate the risks of crop failure under unpredictable and adverse climates (Thorlakson and Neufeldt, 2012; Nguyen et al., 2013), and increase food stability (Charles et al., 2014). The household income generated through selling these TAFS goods can also increase climate resilience and reduce food insecurity through increased purchasing power (Nguyen et al., 2013; Lasco et al., 2016; Quandt et al., 2018). In addition, TAFS can quicken household economic recovery rates post-climate impact by supplying products, such as timber and livestock, for selling when cash is needed, which shortens recovery times (Simelton et al., 2015).

The above benefits provided by TAFS imply that farmers using these systems may be generally more climate-resilient than farmers engaged in open farming systems (Pramova et al., 2012; Thorlakson and Neufeldt, 2012; Pandey et al., 2015; Lasco et al., 2016; Quandt et al., 2018). However, studies assessing agroforestry benefits (Brown et al., 2018; Kuyah et al., 2019) and climate resilience (Linger, 2014; Paul et al., 2017) often use open farming as a control group. Whilst these studies provide important insight into whether TAFS could increase farmers' climate resilience relative to open farming, these studies do not explicitly assess the impacts of climate change on TAFS. Instead, these studies examine relative differences in resilience under climate change to elucidate TAFS' benefits. Consequently, less is known about exactly how climate change will impact agroforestry systems themselves (Neufeldt et al., 2012; Coulibaly et al., 2014; Odeny et al., 2019).

Over the last decade, however, there has been a recognition that increasing temperatures, carbon dioxide levels and changes in humidity and rainfall could affect agroforestry systems (Luedeling et al., 2014; Mbow et al., 2014). Climate change may shift ecological zones in tropical mountains and affect tree species distributions (Lin et al., 2013; Ranjitkar et al., 2016). Tropical tree growth and survival may also be impacted through effects on photosynthesis, respiration, and nutrient

cycles (Siyum, 2020), as evidenced by non-agroforestry tree-based studies (e.g., Yin et al., 2018). If observed on TAFS trees, such impacts would likely affect the ecosystem services supporting farmers' climate resilience. Furthermore, as tree-soil-crop interactions mediate crop production in TAFS, the possibility of resource competition between trees and crops has generated much debate on whether agroforestry benefits crop yields (Bayala et al., 2019). In any case, the impact of agroforestry on crop yields are likely to hinge upon external environmental factors, including temperature and precipitation (Tscharnke et al., 2011; Bardgett et al., 2013; Blaser et al., 2018), which implies that climate change could impact crop yields in TAFS.

Regarding long-term adaptation planning in TAFS for climate change, we need clear evidence on whether and how the changing weather conditions can affect the systems. We systematically reviewed academic research on the effects of climate change on TAFS returned from our search string to identify gaps in current knowledge and to guide future research directions. Specifically, we mapped how the climate change research in TAFS is distributed by geographic region, country, methodology (i.e., empirical or modeling), and approach (i.e., biophysical, livelihoods, or interdisciplinary). We assessed the reliability of evidence presented in all research and summarized the impacts of climate change on the trees, soils and crops in TAFS, as well as the effects on livelihoods under the systems. Lastly, we proposed a study approach and an associated conceptual model to guide research priorities for addressing the identified knowledge gaps and improving the reliability of evidence.

Methods

Systematic review

In July 2022, we conducted a search of academic literature using three academic databases (Web of Science's core collection, Scopus, and Google Scholar) following guidance from the ROSES systematic review protocol (Haddaway et al., 2018) (Figure 1). We tested various combinations of keywords combined with appropriate Boolean operators and wildcards that returned hits that covered a range of impacts that could be linked with climate change, for example, drought. The final search terms applied were ("climat* change" OR "global warming" OR "temperature ris*" OR "temperature increas*" OR "climat* vari*" OR "rainfall dec*" OR "rainfall increas*" OR "rainfall vari*" OR "drought" OR "flood*") AND ("tropic*") AND ("agroforest*" OR "farm tree*" OR "homegarden*" OR "home garden*" OR "taungya" OR "alley farm*" OR "alley crop*" OR "multipurpos* tree*" OR "woodlot*" OR "hedgerow*" OR "improv* fallow*"). The search returned 1,071 hits which were then reduced to 728 once hits were refined to peer-reviewed published articles and duplicates were removed.

We refined our sample to include only published articles to ensure that the reviewed literature had been peer-reviewed as an initial quality control check.

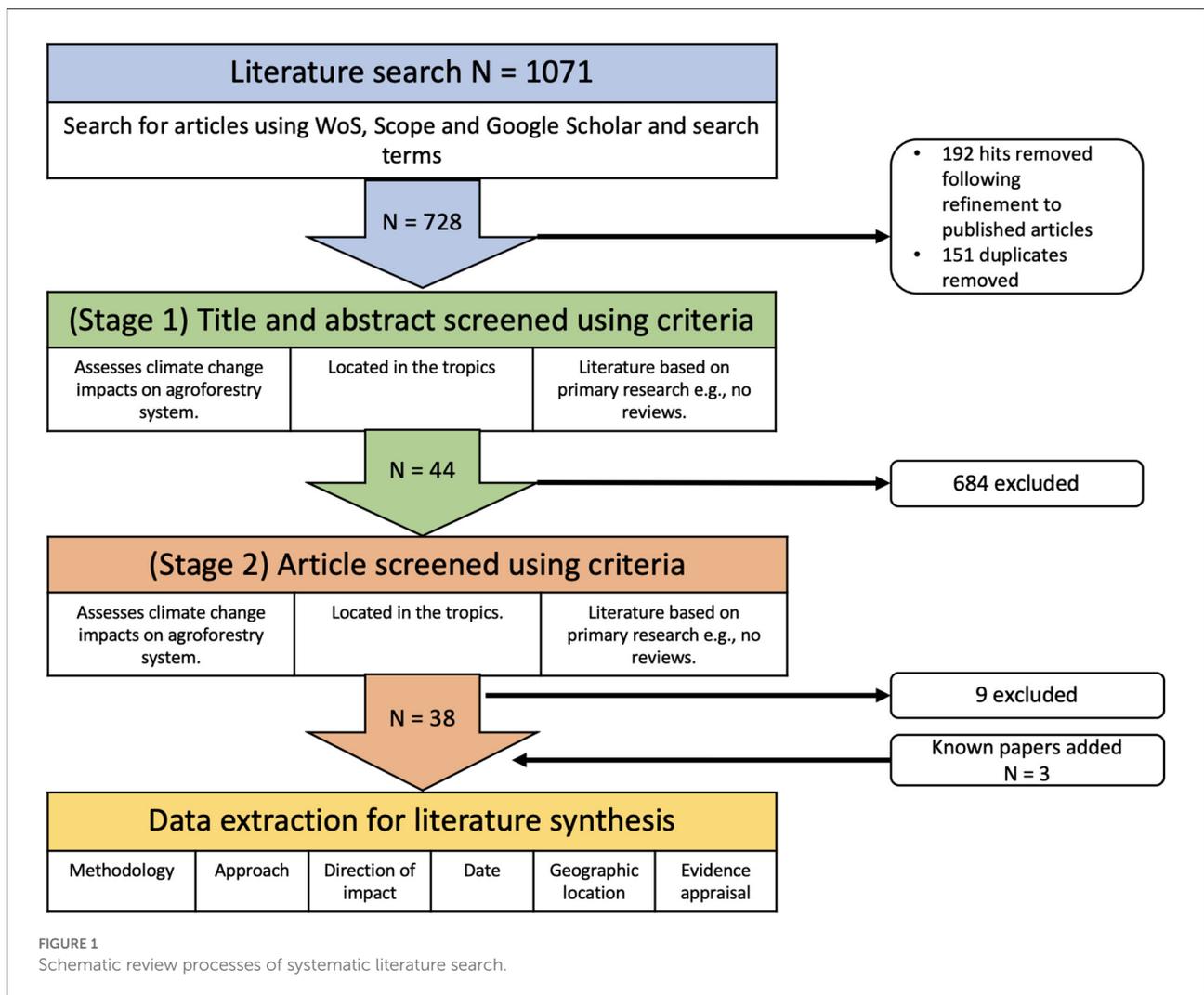
For the inclusion criteria, we applied the criteria that studies should consider one or more aspects of climate change impacts on agroforestry systems, including farmers themselves, in the tropics. Additionally, articles should be based on primary research, which means that review papers were omitted. We also omitted studies that assessed the impacts of climate change on trees not associated with agroforestry in the article. These criteria were applied in a two-stage filtering process, first to the returned abstracts and next in a full paper screening. For the hits returned from the Google Scholar search, these were ordered by relevance (high to low), and only the first 100 hits were reviewed to check that no hits had been missed in the primary databases. Also, relevant papers known to the authors which meet these criteria not returned in the search were added before data extraction. For data extraction, we classified the primary methodology that studies used, for example, whether studies conducted modeling or empirical data collection and analysis, what type of approach was used to discern the impacts [either livelihoods, biophysical, or interdisciplinary (considering both the livelihoods and biophysical impacts)], the direction of impacts (either positive, negative or no effect), and the year and location of the study.

Assessment of evidence quality

To critically assess the evidence provided by published articles, we followed an adapted version of the evidence assessment tool proposed by Mupepele et al. (2016) for ecosystem services and conservation studies. The evidence assessment tool scores the individual quality of studies based on study design and its execution. Studies are then categorized according to an evidence hierarchy based on their individual score (Figure 2).

Assessment of study design

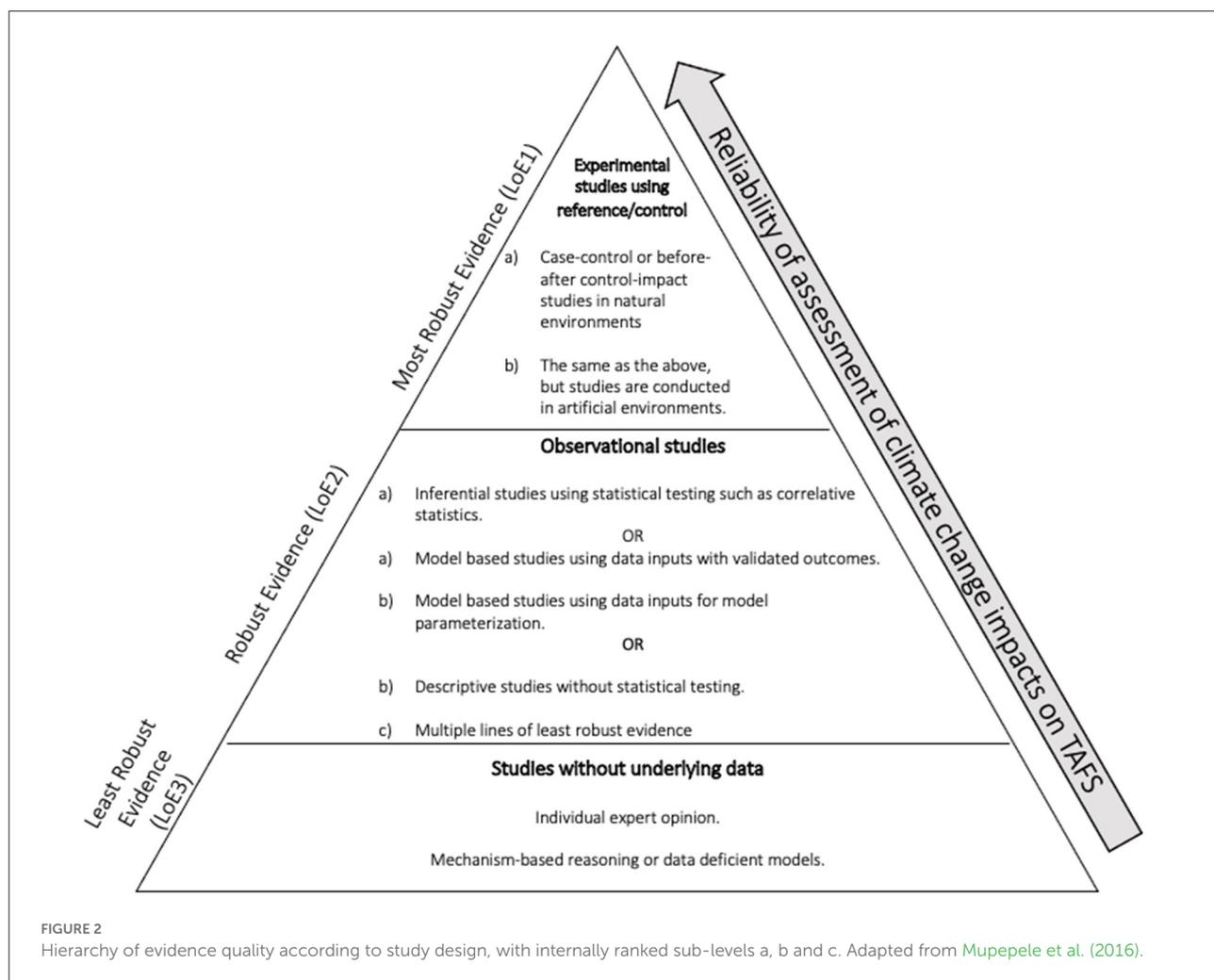
We designated experimental studies employing group or before-after controls as the most robust sources of level of evidence (LoE1), i.e., studies where the TAFS is exposed to a climate parameter representing climate change. The impacts of climate change are assessed relative to a control TAFS or when an open farming system is used to highlight the impacts specifically on the TAFS. Within LoE1, experimental studies performed in natural environments provide the highest level of evidence (LoE1a), whilst experimental studies performed in artificial environments provide slightly less robust evidence, and thus were placed in LoE1b. Experimental studies conducted in artificial environments may not capture agroforestry's cross-scale effects' (van Noordwijk et al., 1996) and can neglect broader



real-world interactions and effects that can influence study outcomes (Coe et al., 2014; Coulibaly et al., 2017). Nevertheless, such studies performed in artificial environments can more precisely assess the effect of climate factors on TAFS and can better associate the recorded impacts with climate change by simulating changes expected over more extended periods, i.e., more than 10 years.

The next level of evidence is “robust” (LoE2), which comprises observational study designs (Mupepele et al., 2016). Within this level of evidence, studies which draw inferences from correlative statistical testing are ranked LoE2a. For example, studies which statistically test the influence of a changing climate parameter on the quantity of a TAFS ecosystem service such as tree fruit production. Descriptive studies without statistical testing, such as studies presenting frequencies or data summaries, that provide weaker association between climate change and TAFS provide slightly less robust evidence, and were subsequently placed in LoE2b.

Modeling-based studies are commonly employed in climate change research to predict the impacts of anticipated future climate conditions. However, modeling the impacts of climate change on complex tree-soil-crop interactions in agroforests can produce uncertain predictions (Luedeling et al., 2014). Studies using modeling designs can therefore produce less robust evidence than empirical experimental studies, and thus were placed in LoE2. Within LoE2, model predictions made using field data for model parameterization and have corroborated predictions produce the most robust evidence (LoE2a), whilst model predictions not validated produce less robust evidence (LoE2b) (Mupepele et al., 2016). These standards are pertinent to TAFS modeling-based studies because to make inferences for the targeted TAFS, the data used should derive from the study site. Furthermore, given the levels of uncertainty in modeling approaches for projecting climate change impacts on TAFS, corroborating model predictions is key for proving evidence reliability. Predictions made from mechanistic models lacking



field data produce the least robust evidence for discerning the effects of climate change on TAFS (LoE3), alongside expert opinion ([Mupepele et al., 2016](#)). However, multiple lines of LoE3 evidence can increase study reliability to robust levels of evidence (LoE2c).

Critical appraisal of study design implementation

Singularly considering study design as an indication of evidence quality is insufficient because the execution of the methodology may have been less rigorous ([Rychetnik et al., 2002](#)). Consequently, a critical appraisal of the implementation of the study design was also undertaken using the methodological quality checklist developed by [Mupepele et al. \(2016\)](#). This checklist was devised using information from 30 published quality checklists known for evaluating evidence-based practice. The aspects covered include setting the research aim, data collection, analysis, presentation of results

and the conclusions drawn and more specific questions for some individual studies based on their design (e.g., control group studies have an additional five checklist questions). This seeks to highlight any bias and inferential error impacting the validity of the evidence. The checklist, however, does not provide specific detailed questions for all study approaches (for example, there are no specific questions for modeling-based studies) and so should not be considered entirely comprehensive ([Mupepele et al., 2016](#)). However, the aforementioned criteria were deemed sufficient to appraise all modeling and non-modeling studies included in our review.

We used the quality checklist to derive a percentage score for each study (each question answered “Yes” = 1 point; “No” = 0 points). Questions not applicable to a study given its methodology were not factored into the percentage score. Depending on the score, the study can be moved down a sub-category or category due to a less rigorous execution of study design (see [Table 2](#)). The amalgamation of the study design ([Figure 2](#)) and quality checklist score is the final step

TABLE 2 Movement of level of evidence based on percentage scored in quality checklist.

Percentage score	Moved down in LoE
>87%	None
75–87%	By half a level (e.g., LoE1a to LoE1b)
62–74%	A whole level (e.g., LoE1a to LoE2a)
50–61%	By one and a half levels
37–49%	By two levels
25–36%	By two and a half levels
<24%	By three levels

Adapted from Mupepele et al. (2016).

to determine the quality of evidence for supporting the study conclusions (Mupepele et al., 2016).

Results

Descriptive statistics of published articles

A total of 35 studies were retained following the search and two-stage inclusion criteria (Figure 1). Three known papers, which did not explicitly mention climate change-related terms and tropical agroforestry in the title or abstract, but assessed the impacts, were added, bringing the total to 38 studies. Regarding the methodology used, most studies undertook empirical data analysis ($n = 33$), with much fewer undertaking modeling ($n = 5$) which focused on simulating the future impacts of climate change (Figure 3A). By year there has been an increase in the number of published papers over the last decade, with the numbers of papers peaking in 2018 ($n = 6$) and 2019 ($n = 5$) (Figure 3B). Most studies undertook a biophysical approach to assess the impacts of climate change ($n = 31$), whilst fewer undertook an interdisciplinary ($n = 6$) or livelihoods approach ($n = 1$) (Figure 3C). In total, most studies found that the impacts of climate change were negative ($n = 27$), and only a minority of studies concluded either no effect ($n = 9$) or a positive impact ($n = 2$) (Figure 3D). Geographically, studies have been conducted in South and North America, Eastern and Western Africa, and South and Southeast Asia, with most studies conducted in India ($n = 6$) and Indonesia ($n = 5$) respectively (Figure 4).

Assessment of the evidence on the impacts of climate change on TAFS

Based purely on study design, studies providing LoE2a strength evidence are the most common ($n = 13$, 34.2%), which could be accredited to climate events, such as droughts, providing the conditions required to assess the effect of climate on TAFS. Next most common are studies providing

LoE1b ($n = 10$, 26.3%) and LoE2b ($n = 10$, 26.3%) strength evidence (Figure 5A). No LoE3 study designs were found, and no modeling-based studies using field data corroborated their predicted impacts of climate change, which limited their evidence to LoE2b.

Following the appraisal of methodological quality, most studies were moved down in their LoE ($n = 32$, 84.2%) and 20 (62.5%) studies were moved down by a whole level or more (Figure 5B). This indicates that studies assessing the climate change impacts on TAFS commonly lack rigor in their execution, which could be due to their difficulty and costliness to set-up and implement in the field, and supports the notion that assessing study design alone is insufficient to determine evidence quality. Overall, studies performed well in data collection aspects such as defining the study population of interest and mitigating detection bias, as well as ensuring that their conclusions were well supported by the evidence. Studies performed less well in data collection aspects such as blind sampling, randomly allocating case-control groups, ensuring any surveys (if used) were piloted and secondary data (if used) were critically evaluated before use. By study design, modeling studies were implemented most reliably, scoring on average 83%, followed by experimental control group approaches (75%) and observation studies (66%). The lack of specific checklist criteria for modeling did not likely influence scores because experimental control group approaches scored on average 9% higher than observational studies despite having more criteria (5 compared to 1). Our synthesis of the literature presented in the following sections are mainly based on LoE3 strength evidence ($n = 14$) followed by LoE2a and LoE2b strength evidence ($n = 10$ each), with few cases of LoE1 strength evidence ($n = 2$) (Figure 5B).

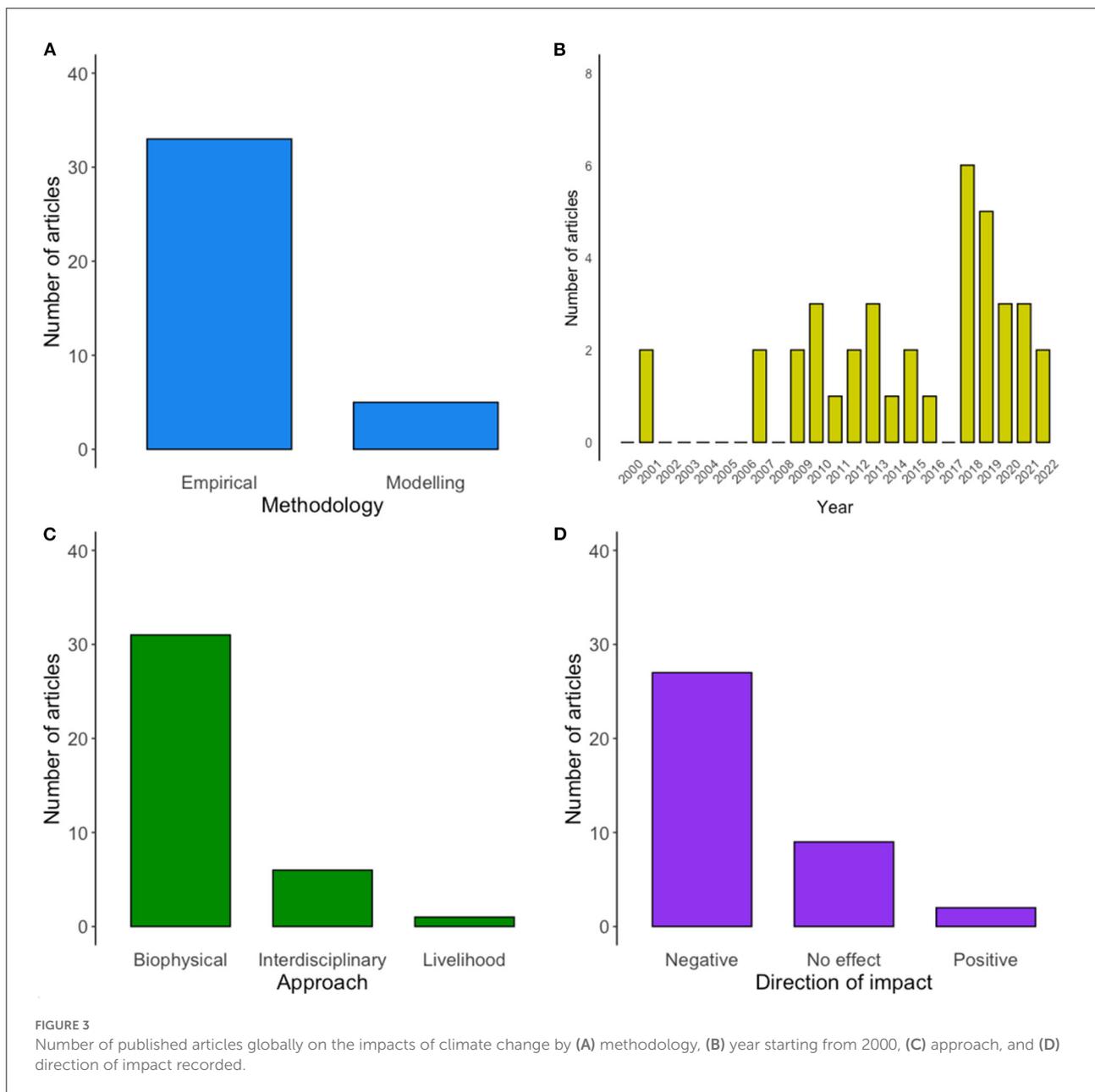
The impact of climate change on TAFS

Studies using a biophysical approach to assess the impacts of climate change on TAFS

The impacts recorded in these studies are grouped under four themes that emerged during data synthesis: TAFS trees (including tree growth, distribution and mortality), tree fruit production, soils, and tree-soil-crop interactions. Some studies involved cross-cutting themes.

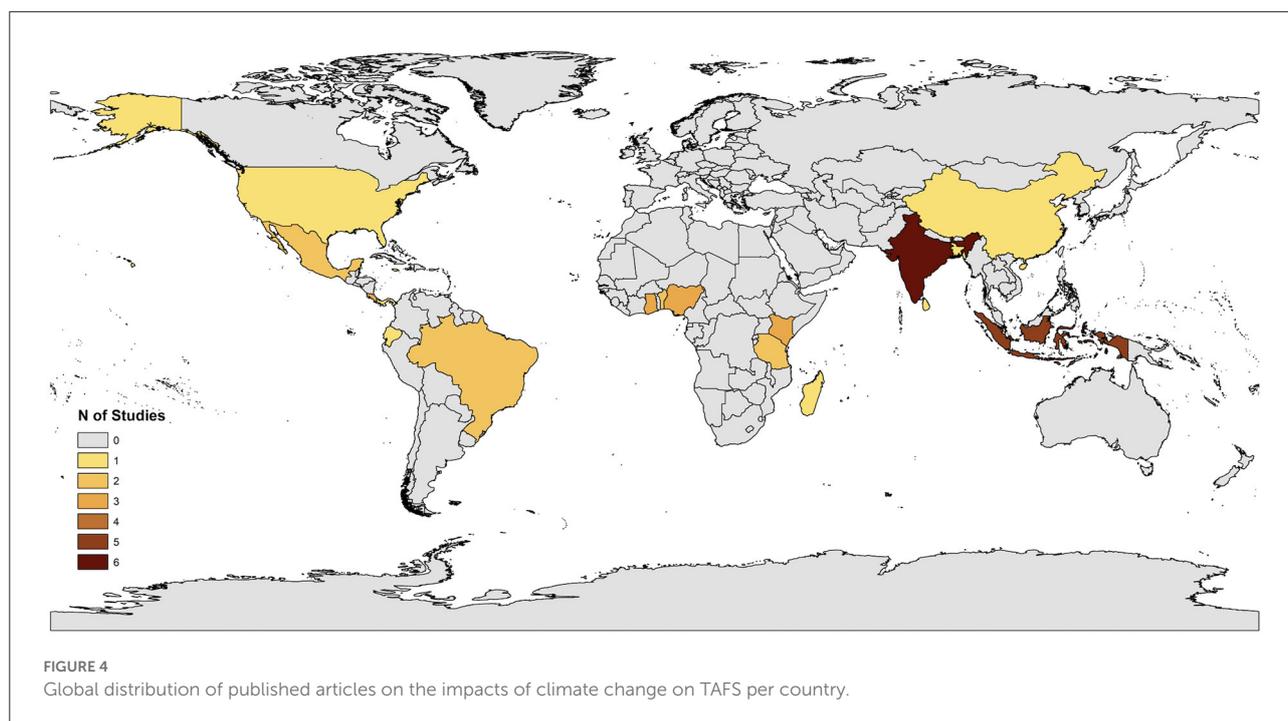
The impacts of climate change on TAFS trees

Our knowledge about the impacts of climate change on tree growth and distributions is based on LoE2a, LoE2b, and LoE3 strength evidence. LoE2a evidence from several studies indicate that reduced rainfall, water stress and increasing drought severity, which are expected under climate change, could limit the height and root growth of trees and plants in TAFS, including *Amomum villosum* (Feng and Li, 2007), *Azadirachta indica* (Puri and Swamy, 2001), *Tectona grandis* (Kumar et al., 2021),



Guazuma ulmifolia, *Albizia lebbeck*, *Leucaena leucocephala*, *Piscidia piscipula* and *Lysiloma latisiliquum* (Tamayo-Chim et al., 2012). Although the consensus in these studies is that drought can negatively affect tree growth, some evidence revealed slight variation in responses. Legume tree species, for example, can exhibit greater resilience to mild drought than non-legumes (Tamayo-Chim et al., 2012). Compared to *Tectona grandis*, the growth rate of *Acacia mangium* and *Eucalyptus camaldulensis* was not significantly affected by reduced amounts of rainfall although their ability to sequester carbon declined (Kumar et al., 2021). In addition, LoE2b strength evidence revealed that *Leucaena leucocephala* seedling

growth is negatively impacted by drought. However, these impacts are reduced in seedlings infected with *Rhizobium tropici* (root nodule bacteria) (Pereyra et al., 2015). On the contrary, we also have LoE2a strength evidence, which suggest that climate change, manifested through a combined effect of increased atmospheric temperatures and elevated CO₂, could benefit trees species (*Cedrela odorata* and *Gliricidia sepium*) in terms of faster growth (Esmail and Oelbermann, 2011). However, the increased growth rate comes with a trade-off: the reduction of leaf nutrient value. Less robust evidence indicates that increased temperatures, drought, and decreased annual rainfall can impair the seed germination of *Garcinia kola* to the point



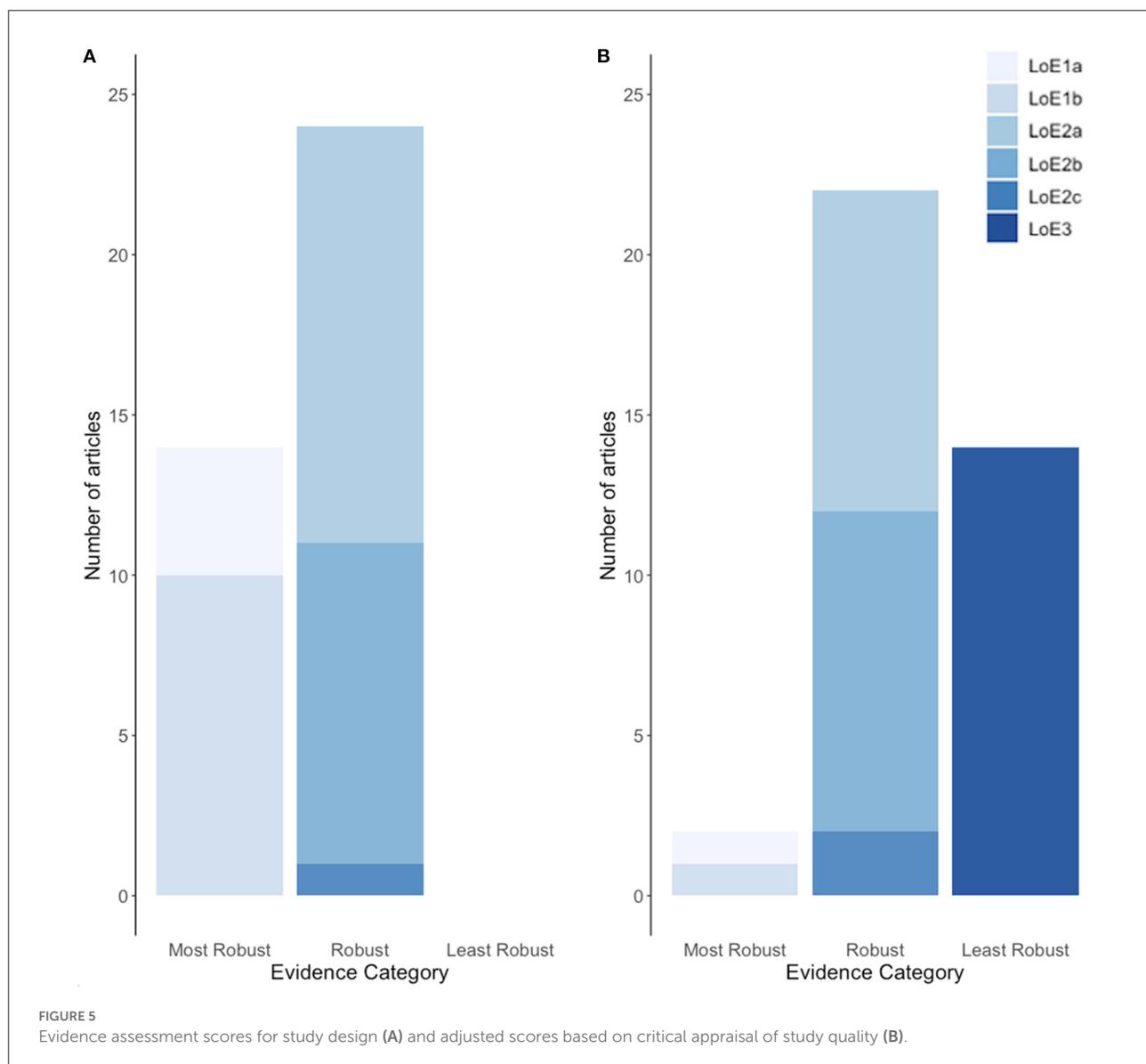
that agroforestry farmers no longer plant the tree species to gain tree fruit (Agwu et al., 2018). Overall, the current evidence denotes that climate change is likely to negatively affect tree and plant growth in TAFS, albeit with some intra-species variation. Our evidence also suggests that legumes and trees infected with symbiotic bacteria could be more resilient to drought impacts.

According to LoE2b strength evidence, whether a future climate scenario entailing warmer temperatures and higher annual rainfall drives the upslope or downslope migration of tree species in montane environments and changes in their aboveground carbon can depend on emission scenarios and TAFS geographic location. For example, under RCP 4.5 projections in Tanzania, suitable climate conditions could shift upslope for *Albizia gummifera* and *Persea americana* and downslope for *Mangifera indica*, though under RCP 8.5 projections, suitable climate conditions for *Persea americana* could shift downslope (Odeny et al., 2019). Whether these tree species increase or decrease in their aboveground carbon may also vary depending on the different future climate scenarios they are exposed to; however, in Kenya, all these tree species except *Albizia gummifera* may decline in aboveground carbon irrespective of the different climate scenarios. In contrast, similarly robust evidence suggests that aboveground carbon in TAFS in India could remain unchanged (Russell and Kumar, 2019), whilst in Nigeria forecasted declines in rainfall amounts during the hottest months could reduce the land suitable for supporting *Garcinia kola* by up to 35.8% based on LoE3 evidence (Agwu et al., 2020). These findings indicate that the future

impacts of climate change could be positive, negative or have no effect on tree distribution and size.

We found varied results concerning the impacts of climate change on the abundance and size of trees at the species level in TAFS. The abundance of *Vitex doniana* was unaffected by differences in climates comprising wet, intermediate, and dry climatic conditions (Hounkpèvi et al., 2018). However, the size of *Vitex doniana* significantly differed across different land cover types, but only those found in cropland significantly differed across climatic zones. This LoE2a strength evidence suggests that land cover type mainly effects the size of *Vitex doniana*, but climate change may impact *Vitex doniana* size if it is grown in croplands. In contrast, slightly less robust evidence (LoE2b) suggests that climate change through drought significantly and negatively affects tree size at the species level in TAFS (Vincent et al., 2009). The extent of decrease in size linked with drought varied according to the tree species and size. For example, *Saurauia nudiflora*, a large tree, declined by 80% in diameter at breast height compared to a 5% decrease in the smaller *Archidendron bubalinum*. The divergence in findings across these studies may be due to interspecies variation in responses to changes in climate conditions, as well as the harsher change in climate under drought.

The relationship between drought induced by climate change and tree mortality is equivocal. We found LoE2a strength evidence that severe drought can increase tree seedling mortality by 35–40% due to the inability to match transpiration demands (Puri and Swamy, 2001). However, equally robust evidence



suggests that exposure to drought does not increase tree seedling mortality, despite impairments in their growth (Tamayo-Chim et al., 2012). We found similar discrepancies in studies reporting LoE2b strength evidence. For example, Gateau-Rey et al. (2018) found that drought could increase tree mortality for cacao trees and their shade trees in Brazil, implying that tree shading may not be effective against drought. Yet, Vincent et al. (2009) found no link between climate change-induced drought and tree mortality despite the extreme event clearly reducing tree size. Such discrepancies may be due to interspecies variation in responses to drought, for example, by reducing their size to adapt to drought and differences in drought severity. We also have 'least robust' evidence (LoE3), which shows that other climate extremes concerning flooding increase tree mortality in cacao TAFS. Tree mortality associated with flooding can be

nanced by age, however, with older TAFS potentially more vulnerable (Somarrriba et al., 2001).

Impacts of climate change on tree fruit production in TAFS

A climate resilience benefit of TAFS is the ability to supply tree fruits and products to smallholder farmers when the climatic condition for crop production is not favorable. However, extreme weather induced by climate change can also negatively affect fruit production. This is supported by both robust (Schwendenmann et al., 2010; Peters and Carroll, 2012; Arnold et al., 2018; Gateau-Rey et al., 2018) and least robust evidence (Boissière et al., 2013; Tregidgo et al., 2020; Wagner et al., 2021).

Drought could decrease cacao yields by reducing the production of cacao pods per tree, often through outbreaks of disease (Gateau-Rey et al., 2018). However, LoE2a evidence indicates that declines in cacao yields in TAFS under drought are unlikely to be driven by disease (Schwendenmann et al., 2010). Instead, drought could reduce cacao disease outbreaks by creating less moist and humid environments, suggesting that other factors associated with climate may reduce cacao yields. We also have robust evidence demonstrating that both climate extremes (wet and dry) could negatively impact fruit production in TAFS by affecting pollinators. More intense and unpredictable rainfall can adversely impact coffee yields by increasing coffee flowering at times asynchronous with bee pollinators (Peters and Carroll, 2012). Drought can also hinder cacao yields in TAFS by depleting moisture needed for *Ceratopogonidae* (cacao midges and pollinators) larvae, reducing their abundance (Arnold et al., 2018). Our least robust evidence suggested that extreme hot weather could also reduce acai fruit production by preventing the trees from bearing fruits (Tregidgo et al., 2020), and severe storms could destroy fruit trees in homegardens and cause a direct loss of fruit production (Boissière et al., 2013). Equally weak evidence, however, suggests that it is unlikely that higher temperatures and increasing rainfall would increase the prevalence of coffee tree pests in TAFS (Jaramillo et al., 2013), though coffee fruit size and quality are still likely to decline from the associated accelerated ripening (Wagner et al., 2021).

Impacts of climate change on soils in TAFS

Our knowledge of the impacts of climate change on TAFS soils is based on most robust (LoE1a), robust (LoE2a to LoE2b) and least robust (LoE3) evidence. According to the most robust evidence, drought could negatively impact TAFS soils by reducing plant coverage and subsequently soil biota which are needed for soil nutrient cycles (Lakshmi et al., 2021). This is congruent with robust evidence which suggests that drought could reduce soil biota productivity in TAFS, as indicated by declining soil CO₂ efflux, although only under severe drought (van Straaten et al., 2010). Similarly, model simulations suggested that increases in air temperature will drastically decrease soil C content, but only under a considerable temperature increase (+6°C) as opposed to a marginal increase (+2°C) (Russell and Kumar, 2019). In contrast, Andriamananjara et al. (2019) suggested that temperature increase (+10°C) will increase soil C and N content, possibly through increased soil biota activity and mineralization rates. However, this finding was based on an artificial experiment that maintained soil moisture at a constant level and may not properly reflect what occurs in TAFS soils when exposed to hotter climates, as well as less robust evidence (LoE3). Hence, increasing temperature is more likely to reduce soil C and biota activity productivity in TAFS based on the more reliable evidence. Concerning forecasted increases in rainfall amounts

and intensity, the associated flooding and increased run-off could significantly increase soil nutrient loss and erosion in TAFS, as indicated by LoE2b (Choudhury et al., 2022) and LoE3 (Balasubramanian et al., 2015) strength evidence. Soil erosion in TAFS, however, may be less severe than in open farming systems (Choudhury et al., 2022). Overall, we cannot conclusively assert that climate change would negatively affect soils due to a limited number of soil properties assessed by only six studies.

Impacts of climate change on tree-soil-crop interactions in TAFS

Whether climate change negatively affects tree-soil-crop interactions in TAFS can depend on the crop type, the tree species and the study design used to assess the impact. We found LoE1b strength evidence which demonstrated that drought can negatively influence tree-soil-crop interactions in cacao TAFS (Blaser et al., 2018). We also have LoE2a strength evidence supporting similar findings in cacao TAFS which encompassed *Albizia ferruginea* and *Antiaris toxicaria* shade trees (Abdulai et al., 2018). Under warmer and water-limited environmental conditions, competition between trees and cacao plants for scarce soil water resources intensified (Blaser et al., 2018). This can reduce soil moisture and cacao yields below levels in open-sun cacao farms. Drought conditions have also been shown to cause more significant water loss in cacao TAFS than in open-sun cacao farms as a result of the combined transpiration rates of both cacao plants and trees (Abdulai et al., 2018). This, in turn, intensifies water resource competition and can lead to cacao plant mortality. Similar resource competition for limited soil water has also been reported in maize and *Grevillea robusta* TAFS, which delays the flowering and development of maize and can lead to crop failure (Lott et al., 2009).

On the other hand, we also have LoE2a (Schwendenmann et al., 2010; Muñoz-Villers et al., 2020) and LoE2c (Köhler et al., 2010) strength evidence which implied that cacao and coffee in TAFS were not impacted by drought. Contrary to Blaser et al. (2018) and Abdulai et al. (2018), Schwendenmann et al. (2010) and Köhler et al. (2010) found that when cacao is cultivated with *Gliricidia*, water stress in cacao plants is low. This can be due to shading effects and complementary root structures, which involve crop roots occupying shallow soil layers whilst tree roots extract water from deeper soils. This helps preserve and more efficiently use limited water resources. Their evidence, however, was generated using artificial drought conditions created under roof plots, which can poorly resemble changes in temperature, radiation, and vapor pressure deficits that are also altered by drought (Schwendenmann et al., 2010). Hence, to develop knowledge of how climate change could affect tree-soil-crop interactions in TAFS, more research performed in natural environments using tree species and crops varying in root structures and depths is necessary.

Studies using a livelihood or interdisciplinary approach to assess the impacts of climate change on TAFS

Livelihood approach to assess climate change impacts

We found only one study using a livelihoods approach to assess the impacts of climate change on TAFS (Onyekuru and Marchant, 2016). This model-based assessment provided LoE2c strength evidence that there was no significant impact on household net revenues under the simulated future climate scenario of an increased temperature by 1°C and a 7% decreased annual rainfall in Nigeria. However, a low model R^2 value (0.11) indicated that other important variables influencing net revenue were absent, and the model did not account for biophysical interactions between forests and climate change. Therefore, this assessment could potentially be underestimating the impacts.

Interdisciplinary approach to assess climate change impacts

All six studies using an interdisciplinary approach yielded LoE3 strength evidence. The negative impacts in these studies were mainly analyzed and presented through descriptive summaries of survey data collected in Indonesia (Boissière et al., 2013), Nigeria (Agwu et al., 2018) and Ecuadorian highlands (Córdova et al., 2019). Biophysical impacts identified by these studies included adverse effects on crop yields, fruit production, fodder production, soil moisture, water quality and quantity and biodiversity, whilst the livelihood consequences involved negative effects on livestock, household income, cultural values, health, and the displacement of farmers from increasing temperatures, drought, and declines in annual rainfall. Conversely, a hypothetical study conducted in Hawaii found that the flammability of TAFS and groundwater recharge under this land use is likely not to be affected by increasing temperatures (+ 2°C), whilst farmers could expect higher economic returns for their produce under the warmer climate (Bremer et al., 2018). Similarly, farmers in Benin perceived that ecosystem services from TAFS, such as the supply of raw materials and food production, were unaffected by increases in drought, temperature and rainfall intensity (Belfrid et al., 2022). However, the exact details of how the biophysical and livelihood impacts intersected in these interdisciplinary studies were lacking. Therefore, it is unclear how climate change impacts the TAFS as a social-ecological system as a whole.

In contrast, an interdisciplinary assessment of the impacts of climate change on homegardens in Sri Lanka adopted an interdisciplinary conceptual framework to elucidate how climate change affected interactions and feedback between the homegardens biophysical and livelihood and farm management components (Landreth and Saito, 2014). Guided by their framework, their evidence implies that increasing rainfall variability and intensity enhances soil erosion and landslides and destroys farmers' food crops. In response, farmers then increased their food purchases and partially abandoned their

homegardens. This, in turn, can increase wild animal incursions, further destroying crops and forcing farmers to simplify their crop production to inedible but drought-resistant cash crops. These consequences that negatively affected biodiversity (biophysical) but improved household income (livelihood) signal that climate change can create environmental and livelihood trade-offs in TAFS.

Discussion

The impacts of climate change on TAFS

Our review found that TAFS were mostly negatively affected by climate change. Climate change, manifested through increased temperature, changes in rainfall amounts and intensity and drought, may hinder agroforestry farmers' climate resilience in dealing with the decline in ecosystem services. These ecosystem services from TAFS are necessary to increase farmers' household resilience against climate change (Nguyen et al., 2013; Pandey et al., 2015; Quandt et al., 2017), and our results show that climate change mostly negatively impinges on their provision. To increase their resilience, farmers could plant leguminous trees and other tree species that our review found can be less sensitive to climate change, including *Acacia mangium*, *Eucalyptus camaldulensis*, *Cedrela odorata*, *Gliricidia sepium* and *Vitex doniana*, as well as tree species which support root nodule bacteria.

The negative impacts of climate change, particularly climate change-induced droughts, on tree mortality and growth in TAFS summarized in this review are mainly consistent with some tree-based climate studies in the tropics (e.g., Midgley and Thuiller, 2011; Yin et al., 2018), but contrasted with other studies (Koch and Kaplan, 2022). Concerning the impacts on TAFS fruits and crops, under some cacao-based TAFS droughts can cause lasting post-drought impacts on yields due to increased cacao plant mortality (Abdulai et al., 2018; Gateau-Rey et al., 2018), despite the initial general claim that TAFS quickens household economic recovery post-climate extreme (Simelton et al., 2015). Changes in rainfall amount and timing can also lower yields in TAFS by impeding the growth of fruit trees, crop development, flowering, and pollination (Peters and Carroll, 2012; Agwu et al., 2018; Wagner et al., 2021), with some crops producing much lower yields in TAFS than open farming systems (Lott et al., 2009). However, our review also found evidence suggesting that some TAFS crops may be unaffected by climate change (Köhler et al., 2010; Jaramillo et al., 2013), albeit supported by less robust evidence. Our limited evidence on the impacts to TAFS soils suggested that whether drought also negatively impacts TAFS soils could depend on drought severity. However, our knowledge regarding the impacts on soil is restricted by only a paucity of relevant studies. This also holds for our knowledge of the impacts of climate change on livelihoods in TAFS.

Concerning current debates on whether tree-soil-crop interactions in TAFS are complementary or competitive for natural resource use (Bayala et al., 2019), the findings from our review implied that under drought and water-limited environmental conditions, interactions can depend on tree-crop root systems. Robust evidence derived through field experiments reinforced some experts' opinions that climate change could impact ecological interactions in agroforests (Tscharnkte et al., 2011; Luedeling et al., 2014). This could have implications for adaptation to climate change as positive climate buffering effects in TAFS could be outweighed by negative effects, including increased water loss and enhanced resource competition. This knowledge, however, was based on a limited number of studies. However, our review also found robust evidence supporting agroforestry proponents who maintain that complementary root structures in TAFS can protect crops against climate change (e.g., van Noordwijk et al., 2021). This evidence, however, was derived through studies mostly conducted in artificial conditions, which may not properly simulate actual drought conditions (e.g., Schwendenmann et al., 2010). The lack of experimental studies in the research field which examine the effects of climate change on tree-soil-crop interactions within TAFS encompassing more complementary root structures in natural environments limits what we are able to conclude from the available evidence.

Reliability of evidence

We found that studies primarily presented either robust (LoE2) or least robust (LoE3) evidence of climate change impacts. The shortage of “most robust” (LoE1) evidence could be due to the difficulty in devising a natural experimental control group approach encompassing different climate conditions. Most experimental controlled studies exploited drought events, which are only one aspect of climate change, or needed to artificially create climate conditions that can limit real-world applicability. However, we still acknowledge the value added by artificial experiment studies' to the field. No modeling-based studies corroborated their predictions, which restricted their predictions to LoE2b. We appreciate, however, that the long-term future climate scenarios targeted in modeling studies can make ground-truthing surveys challenging.

Few studies used a livelihood and interdisciplinary approach, and these studies only presented the least robust (LoE3) evidence. These studies provided limited insight as they only offered a “snapshot” of the impacts at a particular time and mainly displayed the recorded impacts through data frequencies. This restricted our understanding into how climate change was associated with their documented impacts. Agroforestry systems encompass close interactions between their biophysical and social elements (Elbakidze et al., 2021), where impacts on one element will impact the other through mutual relationships and feedbacks (Liu et al., 2007; Ibarra

et al., 2021). Such descriptive and “snapshot” studies which overlook these relationships and feedbacks cannot sufficiently capture the multi-faceted nature of climate change impacts on TAFS. Interdisciplinary conceptual frameworks were shown to have the potential to capture these mechanisms and impacts (Landreth and Saito, 2014).

Limitations

Our review is presented with some limitations. Firstly, our review findings were based on a limited number of studies. We believe, however, that the small sample of relevant studies is an accurate reflection of the current literature on the review topic. Secondly, the findings presented in our review have also been established from English academic literature, which can bias results (Amano et al., 2016). Finally, we did not include gray literature in our review including reports, theses and dissertations, and as such, our findings are representative of published academic research.

Future research priorities

Overall, we found limited evidence on how climate change will impact the ecosystem services provided by TAFS. Particularly understudied areas include the impacts on the livelihoods of smallholders, and their wellbeing (i.e., cultural, material, food and health). Therefore, we are uncertain about the potential adverse impacts of climate change on people in TAFS. Discerning the potential impacts of climate change on crop production in TAFS and farmers' wellbeing is vital for long-term climate change adaptation planning. Trees are long-lived organisms, and their establishment in farmland requires resource investment (Luedeling et al., 2014). Hence, it is important to ascertain whether investing in TAFS can protect farmers in the long term against climate change. However, our review demonstrates that the current evidence from models targeting long-term periods lack corroboration, whilst insight from artificial experiments can omit meaningful broader interactions with the environment and people (Coe et al., 2014; Hounkpèvi et al., 2018) and may not be able to replicate all essential climate variables (Schwendenmann et al., 2010). To advance knowledge on climate change impacts on TAFS as a social ecological system, an ideal field study should consider collectively and in isolation the impacts on the biophysical system (trees, soils, water); social system (e.g., farmers' decisions); tree-soil-crop interactions; ecosystem services (crop provision) and farmers' wellbeing.

Our review also revealed that most studies focused on examining the impacts on one crop, which was often cacao. This is problematic for two reasons. Firstly, cacao is climate-sensitive (Wood and Lass, 1987), and our conclusions drawn

from these publications may be skewed. Secondly, single crop-based systems poorly represent TAFS which are usually highly diverse (Pathak and Dagar, 2000; Jemal et al., 2018). To better represent TAFS in climate change studies, future research could study TAFS which support a diversity of crop types. For example, homegardens are known for their high crop, tree and tree fruit diversity (Kumar and Nair, 2004; Dagar and Tewari, 2017), offering an ideal system. Homegardens would therefore also provide more diverse root structures suitable for natural experimental studies on tree-soil-crop interactions. Such research could help address our identified knowledge gap regarding the dearth of studies investigating climate change impacts on ecological interactions in TAFS comprising deeper and more complementary tree roots.

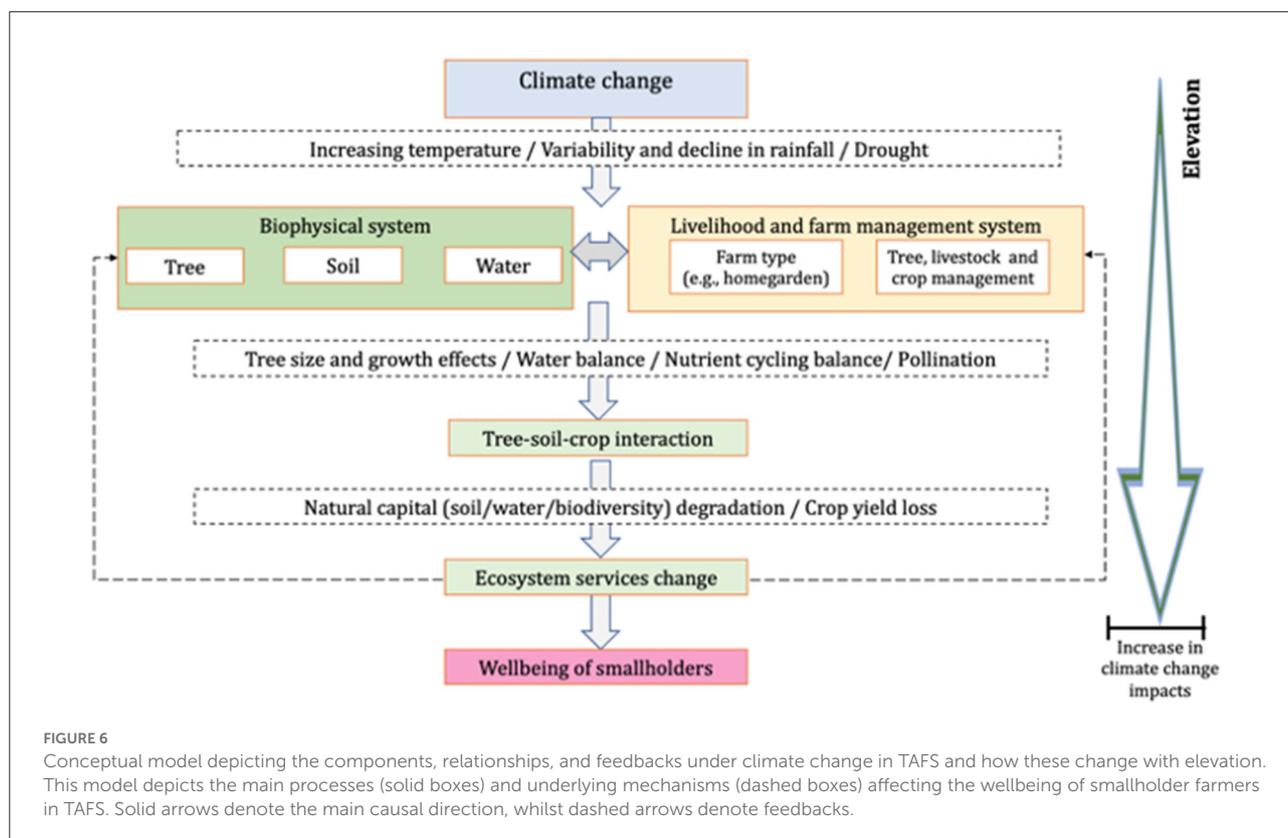
To improve on the robustness of evidence in this research field, we recommend that future research explore the method of climate analog analysis. This involves using various locations where current climates are akin to predicted climates for a site of interest (Veloz et al., 2012). The approach is advocated as an alternative to modeling for projecting future climate impacts on agroforestry systems (Luedeling and Neufeldt, 2012; Luedeling et al., 2014). Mountains in the tropics can be valuable sites for climate analog analysis due to their steep change in climate with altitude. Therefore, experimental studies can use mountain elevation gradients as 'natural laboratories' instead of depending on creating artificial environments (Tito et al., 2020). Downslope locations are typically warmer and dryer, which can resemble drought conditions or future climate scenarios, and can remove the need to create these conditions artificially. The impacts of the change in climate conditions on ecological interactions in agroecosystems in these downslope locations can be more clear than when studied in artificial environments (Tito et al., 2020). Such an approach has been effectively applied to predict the impacts of future climates on crop yields (Tito et al., 2018), soil nutrient cycles (Becker et al., 2015), plant responses (Cardinaux et al., 2018) and soil decomposition processes (Nottingham et al., 2015) in tropical montane forests. Using downslope locations as a climate change treatment can allow studies to assess the impacts of drought, water-limited conditions, and future climate scenarios on TAFS in natural environments more robustly (LoE1a), including on tree-soil-crop interactions, without requiring artificial experiments (LoE1b) or observational study designs (LoE2). Exploiting the change in climate across mountain gradients can allow modeling-based studies focusing on warmer and dryer climates to validate their predictions and improve from LoE2b to LoE2a. Important non-climate and socio-economic factors, however, need to be sufficiently similar across study sites (Feller et al., 2015).

Finally, we recommend following a conceptual model to support the implementation of studies employing a climate analog analysis methodology to predict the response of montane TAFS to climate change (Figure 6). This conceptual model has

been devised using the findings from our review which are based on reliable evidence and where the direction of impact was most consistent. Consistent with our recommendation for interdisciplinary research, our model considers the interactions of both TAFS biophysical and livelihood components in predicting the impacts of climate change. The model considers that provisioning ecosystem services from TAFS and the wellbeing of smallholders are mainly influenced by the tree-soil-crop interactions, which in turn are mediated by (i) the state of the trees, soils, and water in the biophysical system, and (ii) the decisions made in the livelihoods and farm management system (e.g., which trees and crops are planted). We expect the provisioning of ecosystem services and the wellbeing of farmers, including their cultural values, health, and income, to decline under climate change due to impaired tree size and growth (Feng and Li, 2007; Vincent et al., 2009; Tamayo-Chim et al., 2012), declining soil productivity and nutrient cycling (van Straaten et al., 2010; Russell and Kumar, 2019; Lakshmi et al., 2021), reduced water availability (Blaser et al., 2018), lower crop pollination (Arnold et al., 2018) and farmer's decision to change their farm management, which can influence biodiversity (Landreth and Saito, 2014). These biophysical and social impacts would influence tree-soil-crop interactions that underpin smallholder farmers' crop production and wellbeing. Through this dynamic process, and under warmer and dryer climate conditions downslope of mountains, limited soil water could be depleted more rapidly due to resource competition between trees and crops involving less complementary root systems (Lott et al., 2009; Abdulai et al., 2018); and biodiversity could potentially be reduced due to increased plant mortality (Abdulai et al., 2018) and crop failure (Lott et al., 2009). We expect the provision of crops to decrease under increasing climate change impacts (Blaser et al., 2018), and this would then feedback into the biophysical and farm management systems through potential changes in the management of biodiversity and natural resources, or through farmers' responses, such as changing crop types (Landreth and Saito, 2014). Although not included in our review papers, we acknowledge that other socio-economic factors, such as changes in crop market prices, can influence farmers' wellbeing outcomes and crop management choices. Furthermore, as our interdisciplinary papers did not sufficiently study the relationship between farmers' crops and their wellbeing outcomes, the impact on farmers' wellbeing with change in crop provisioning ecosystem service in our conceptual model is informed by the wellbeing-TAFS literature reviewed in our introduction.

Conclusion

Our review has provided a synthesis of the academic literature on the impacts of climate change on TAFS and assessed the quality of their evidence. The key findings are that climate



change impacts on TAFS are under-studied, particularly using a livelihood and interdisciplinary approach, and that our current knowledge is based on robust but also “least robust” evidence. Overall, climate change was found to negatively impact TAFS, which implies that TAFS could still succumb to the adverse effects of climate change if used as a long-term adaptation measure. To ascertain this with more reliable evidence, we recommend that future studies follow an interdisciplinary approach and assess the potential impacts of future climate conditions on TAFS performance using climate analog analysis along mountain elevation gradients.

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.

Author contributions

MW and KP conceived the systematic review. MW and EM conceived the evidence assessment protocol. MW performed the literature search, data extraction, and wrote the manuscript. KP edited the manuscript. All authors discussed results,

contributed to reviewing the manuscript, and approved the submitted version.

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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/ffgc.2022.880621/full#supplementary-material>

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