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Spotlight on agroecological cropping practices to improve the resilience of farming systems: a qualitative review of meta-analytic studies

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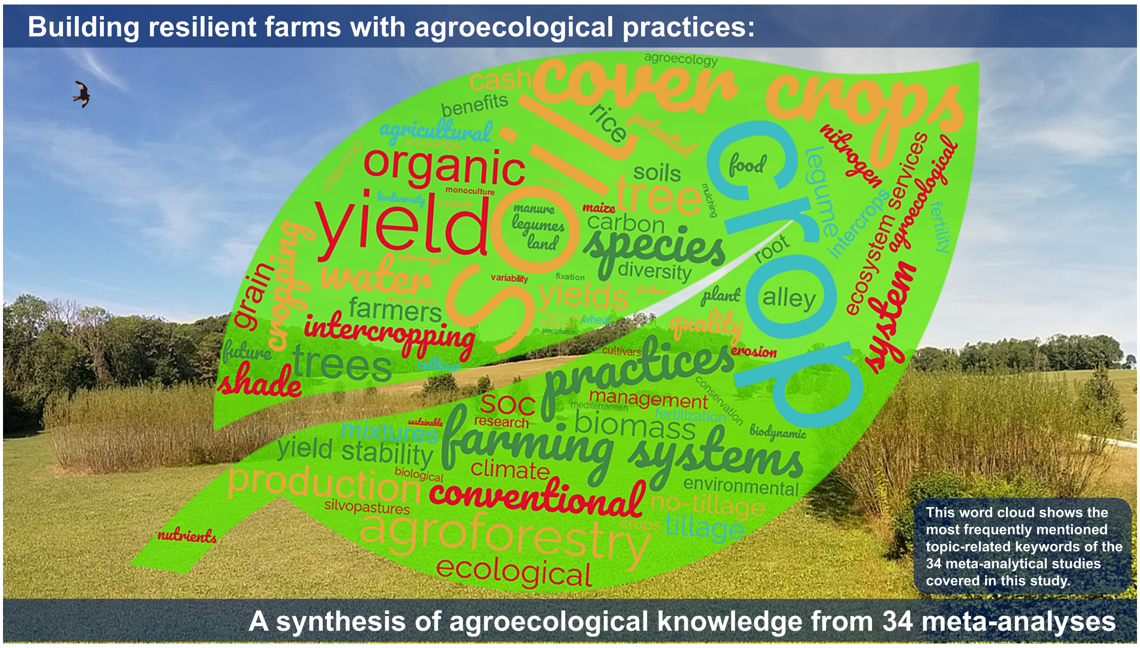
The capacity of agriculture to withstand or recover from increasing stresses (i.e., resilience) will be continuously challenged by extreme climate change events in the coming decades, altering the growing conditions for crop species. By prioritizing natural processes, agroecology seeks to foster climate change adaptation, boost resilience, and contribute to a low-emission agricultural system. Nineteen different agroecological practices using resilience-related terms and "meta-analysis", within the subject areas 'Agriculture and Biological Science' and 'Environmental Science' were addressed, and 34 meta-analyses were reviewed to summarize the state-of-the-art agroecological adaptative strategies applied globally, and the current knowledge gaps on the role of agroecological practices in improving farming system resilience. Two main agroecological strategies stand out: i) crop diversification and ii) ecological soil management. The most frequent diversification practices included agroforestry, intercropping, cover cropping, crop rotation, mixed cropping, mixed farming, and the use of local varieties. Soil management practices included green manure, no-till farming, mulching, and the addition of organic matter. The analyzed studies highlight the complex interplay among soil, plant, climate, management, and socio-economic contexts within the selected agroecological practices. The results varied—positive, null, or negative—depending largely on site-specific factors. Developing and understanding more complex systems in a holistic approach, that integrates plants and animals across multiple trophic levels (feeding relationships, nutrient cycling, and aligning with the principles of a circular economy) is essential. More research is, therefore, needed to understand the interactions between crop diversity and soil management, their impacts on resilience, and how to translate research into practical strategies that farmers can implement effectively.

KEYWORDS

agroecological intensification, conservation agriculture, drought tolerance, intercropping, mixed cropping, soil management, sustainable intensification, traditional knowledge



GRAPHICAL ABSTRACT

1 Introduction

The twin threats of resource overuse/degradation and climate change demand urgent action to preserve and sustain agroecosystems (Pörtner et al., 2022; Rockström et al., 2023). Climate extremes, including rising temperatures, droughts, intensified evapotranspiration, floods, and stronger winds, are already testing the resistance and resilience of farming systems and are fundamentally altering the growing conditions for many crops and this could affect regional and global food security (Kremen and Miles, 2012; Pörtner et al., 2022; Suarez-Gutierrez et al., 2023). However, increasing crop yields through using fossil-derived fertilizers and synthetic chemical pesticides in conventional farming poses significant environmental and social drawbacks. Conventional monoculture systems are highly vulnerable to climate change and contribute substantially to greenhouse gas (GHG) emissions. Despite significant efforts to boost food production, more than 700 million people still face the harsh reality of undernutrition and limited access to nutritious food (FAO, 2025). The global challenge of hunger is not rooted in a lack of food production but in the unequal distribution and accessibility of existing resources. Therefore to reach agroecological resilience it is imperative to address poverty, strengthen food distribution systems, and minimize food waste, creating a world where everyone has access to sufficient nutritious and achievable food (Dow and Reed, 2023). Hence, more sustainable food distribution and consumption are needed in the face of a growing population on a warmer planet (Chaboud and Daviron, 2017; Muscat et al., 2020; United Nations, 2022). Major threats to food systems resilience are global changes (urbanization, aging populations, and climate change) rather than current productivity levels (Tendall et al., 2015). Nevertheless, it also remains important to sustain yields and yield stability, especially in view of the effects of climate change on farming systems.

Unlike conventional agriculture (excess tillage, agrochemicals, monoculture crops), agroecology uses principles to synergize natural and human resources to sustainably produce nutritious and accessible food with little to no chemical-synthetic inputs (Altieri, 2019). Hence, *"the core principles of agroecology include recycling nutrients and energy on the farm, rather than introducing external inputs; enhancing soil organic matter and soil biological activity; diversifying plant species and genetic resources in agroecosystems over time and space; integrating crops and livestock and optimizing interactions and productivity of the total farming system, rather than the yields of individual species (*Gliessman, 2010; FAO, 2011*)."* (Altieri et al., 2017). Furthermore, *"agroecology does not need to be combined with other approaches. Without the need of hybrids and external agrochemical inputs, it has consistently proven capable of sustainably increasing productivity and has far greater potential for fighting hunger, particularly during economic and climatically uncertain times, which in many areas are becoming the norm."* (Altieri et al., 2017).

This includes adopting different practices, such as reducing tillage without herbicides, use of legume species in rotation or as cover crops, organic fertilizers, and crop diversification schemes such as intercropping, agroforestry, grass strips, living barriers, and mixed varieties, among others (Altieri et al., 2017).

A wave of climate and environmental policies is promoting agroecology as a powerful tool in many countries such as Brazil and Colombia. Conducive policies can bolster the health of agricultural ecosystems, paving the way for a sustainable food system and critical climate goals like limiting temperature rise to 1.5°C (DG Agriculture, 2021; Farm to Fork; Biodiversity strategy as part of the EU Green Deal; CAP, 2023). A new partnership between the European Union and the Organization of African, Caribbean, and Pacific States champions agroecology's potential to safeguard biodiversity, nurture healthy ecosystems, and empower communities (European Commission, 2023).

To summarize the state of the art of agroecological practices to enhance agricultural adaptation to climate change employed worldwide, we aimed to identify current knowledge and knowledge gaps in the role of agroecological strategies (crop diversification and ecological soil management) in improving the resistance and resilience of farming systems. This overview intends to contribute to ongoing agroecological research by qualitatively synthesizing the results of meta-analytical studies on agroecological practices. While meta-analyses offer broader insights compared to individual studies, they face challenges such as heterogeneity of data, potential bias, multivariate effects, limited coverage, inclusion of low-quality studies, and the risk of oversimplified or misleading estimates when combining different causal factors (Eysenck, 1994). Individual studies, though informative, often provide site-specific results that may lack reproducibility due to variations in local factors like genetic material, equipment, soil conditions, and climate.

With the advancement of more rigorous meta-analytic methods, their application has expanded, including in ecology. Meta-analyses are now essential not only for synthesizing evidence but also for guiding research design (Borenstein et al., 2009). As the body of published research continues to grow, they play a crucial role in evaluating existing knowledge, identifying research gaps, and refining study methodologies by highlighting the most effective approaches from previous studies. Building on this, the present study aims to discuss existing quantitative syntheses and contribute to the ongoing debate on agroecological practices.

2 Agroecological practices selection

A literature review on 19 different agroecological practices (adapted from (Altieri et al., 2017) to enhance the resilience of agro-ecosystems was carried out on 11 December 2023 using the Scopus® database (Elsevier B.V.) (Supplementary Table 1). The asterisk (*) was used where necessary to find similar spellings of the respective agroecological practices. Primary literature was identified by the "Preferred Reporting Items for Systematic Reviews and Meta-Analyses" method (Page et al., 2021). A refinement using "resilience-related terms" was then carried out, and to further specify the document type, the search string was adapted by adding the term "meta-analysis". Here, "conservation *agr*", "minimum till*", and "no *till*" refer to reduced tillage concepts without herbicide application. Although the use of synthetic plant protection products, such as herbicides and pesticides, is not explicitly prohibited within the framework of agroecology, this work focuses on practices that entirely avoid the use of synthetic products. The search was limited to the subject areas 'Agriculture and Biological Science' and 'Environmental Science'.

In this review, the term metanalysis was included since this type of study combines and statistically analyzes large amounts of data and can offer a clear overview of the impact of a specific treatment over control at a wider scale (Philibert et al., 2012). The total number of documents including meta-analytic studies of agroecological practices and resilience-related terms was 252. These documents were screened firstly for title and abstract, and 199 documents were removed due to various reasons such as (i) no meta-analysis, (ii) focus on other topics (sustainability assessment, modeling studies, etc.), and (iii) non-alignment (e.g., mineral fertilizers allowed, chemical herbicides and pesticides, etc.) with the agroecological farming concept.

The full text of remaining 59 documents were screened and new metanalyses were identified from other sources such as the reference lists of the documents. In total, 34 meta-analyses were included in this review (Supplementary Table 2).

3 Results and discussion

3.1 Crop diversification

3.1.1 Agroforestry

Agroforestry is a crop diversification practice that integrates trees with field crops or pastures (Figure 1). Ngaba et al. (2024) thoroughly (n=125) investigated agroforestry effects on sustainable soil development at a global scale (Figure 2). Across environmental zones, major drivers contributing to global soil fertility were climatic conditions, agroforestry management, tree species selection, biodiversity, crop species selection, soil management, water management, farmer collaboration and training, socio-economic factors, policy support and markets (Figure 2). The meta-analysis of Scordia et al. (2023) on different agroforestry systems across Mediterranean countries (n=161) argued for a negative effect of trees on crop yield that could be ascribed to the competition for light. However, the % change of agroforestry as compared with monocropping was significantly different with tree type (i.e., from -75.8% in ash tree to +3.3% in walnut), with tree cover (from -33.5% with ≥200 trees ha^{-1}) to -8.2% with ≤99 trees ha^{-1}), and with associated crop species (i.e., from -80.8% in the faba bean to +4.5% and +13.1% in the barley and winter wheat). The potential benefits of agroforestry systems under anticipated extreme climate events in the Mediterranean region have been highlighted. While direct evidence of enhanced benefits during such events remains limited, it is hypothesized that the presence of trees may mitigate climatic extremes by reducing wind speed, lowering air temperature, and decreasing crop evapotranspiration (Kanzler et al., 2019; Markwitz et al., 2020). Additionally, in the absence of water stress, moderate shading provided by trees could improve the microclimate for associated field crops, potentially enhancing their resilience and productivity (Scordia et al., 2023).

A recent study by Rodenburg et al. (2022) explored the potential of integrating trees with rice production in Africa. They identified several tree species with broad adaptability and positive effects on rice yields, including *Sesbania rostrata*, *Aeschynomene afraspera*,

FIGURE 1
A silvopastoral agroforestry system experimental field (agroforestry in grasslands) set up in 2009 on the Swabian Alb in south-western Germany is investigating the potential of different woody crop systems to promote the resilience of a agroforestry system on a shallow soil (Rendzina). In this trial, short-rotation willow plantations left (a fast-growing biomass source) are compared with a mixture of local wild tree species right (photo courtesy of Moritz von Cossel).

Acacia auriculiformis, *Gliricidia sepium*, and *Gmelia arborea*. The study found that across all tree-rice systems, rice yields increased by an average of 38% compared to fields without trees. The average tree effect on rice yield (fertilized) was to increase yield by 261 kg ha^{-1} equivalent to a +23% increase at low baseline rice yields (<1500 kg ha^{-1}). However, when the baseline yield was higher (>1500 kg ha^{-1}), the average effect of trees was to decrease rice yield by 519 kg ha^{-1}, equivalent to a decrease of 12%. Notably, some practices provided greater benefits. Biomass transfer and pre-rice green manuring in rice-trees system consistently improved yields. Hedgerow alley-cropping also showed promise, especially when fertilizers weren't used. In fertilized conditions, tree-crop competition negatively impacts yield in systems like hedgerow and intercrop, while non-competing systems (biomass transfer and pre-rice green manuring) show positive exceptions. This suggests that in high-yielding environments, trees may hinder rather than support crop productivity, posing risks to smallholder livelihoods.

Additionally, some tree integration methods like the short fallow practice showed rice yield reductions with fertilizer use. These findings highlight the importance of considering both the type of tree-rice integration and fertilizer use for optimal results. Rodenburg et al. (2022) call for further research to explore the broader environmental, social, and economic impacts of different tree-rice integration methods.

Several other scientific studies have examined the interactions between trees and crops grown in agroforestry systems. These studies shed light on key aspects:

- Firstly, the type of tree species and its root system can significantly influence crop yields. Research by Rivest et al. (2013) indicates that trees with deep tap roots, particularly those that fix nitrogen (N) like *Acacia* species, can benefit nearby crops during droughts through a process known as hydraulic lift. In contrast, trees with shallow root systems, like *Eucalyptus*, compete with crops for water, potentially reducing crop production. Interestingly, studies on scattered deciduous and evergreen oak trees showed no net change in pasture yields (Rivest et al., 2013).
- Secondly, the distance between crops and trees within an agroforestry system plays a critical role in determining crop yield. Meta-analyses by both Van Vooren et al. (2016) and Ivezić et al. (2021) highlight the importance of this spatial arrangement. In temperate alley-cropping and hedgerow systems, crop yields ranged from 70% over a distance of 1.64 times the tree height (when planted very close to trees) to 107% between 1.64 and 9.52 times the tree height (Van Vooren et al., 2016). Ivezić et al. (2021) modeled a 0.56% relative crop yield increase by each additional meter distance to the nearest tree.
- Thirdly, Ivezić et al. (2021) identified additional factors that can influence crop yield in agroforestry systems. Their research suggests that crop yield likely decreases with increasing tree density and tree age within alley-cropping systems. Furthermore, cereal crops generally outperform fodder crops when grown alongside trees in these systems.

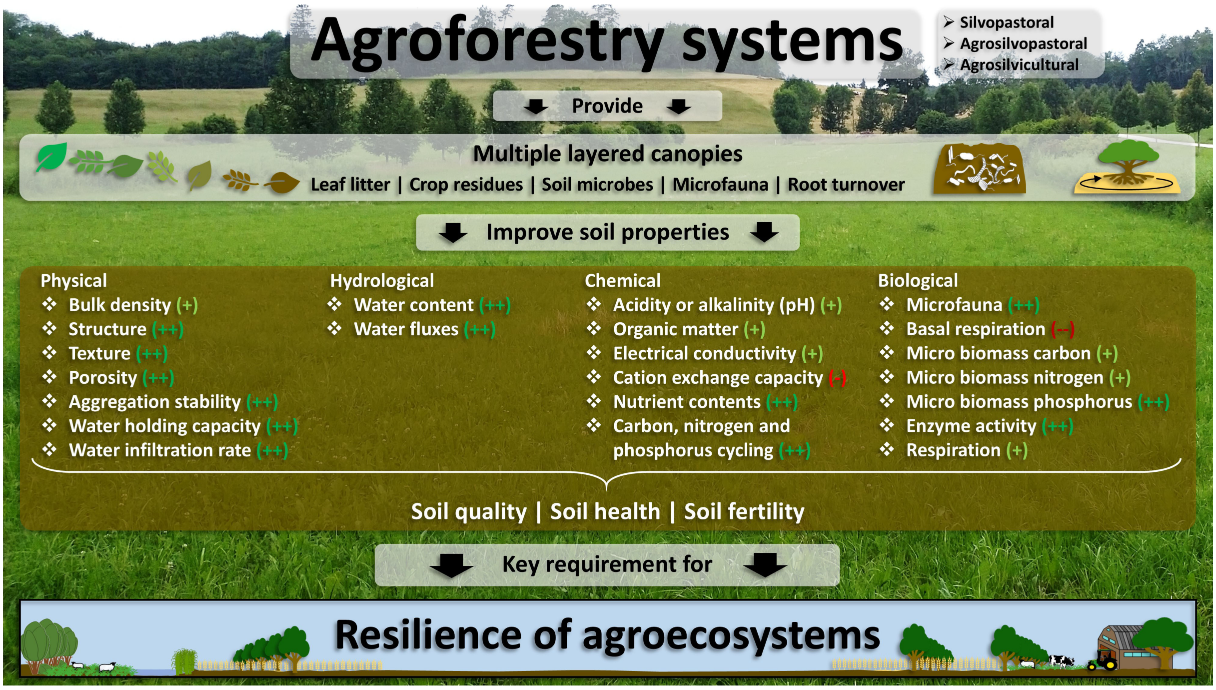


FIGURE 2
Agroforestry-mediated soil amelioration: a graphical representation. This diagram summarizes the hypothesized effects of various agroforestry techniques on soil characteristics. Directional arrows denote causal links, with symbols signifying the anticipated level of improvement across diverse climates: (–) no improvement across all climatic zones, (-) no improvement in specific climatic zone, (+) improvement in specific climatic zone, (++) consistent improvement in all climatic zones. Key soil variables include organic matter (OM), electrical conductivity (EC), and cation exchange capacity (CEC) (adapted from: Ngaba et al., 2024).

Interestingly, the relative response of crop yield appeared similar in both northern and southern European agroforestry settings (Ivezić et al., 2021).

- Finally, a recent study by Koutouleas et al. (2022) focused on the impact of shade on coffee production in agroforestry systems. Their meta-analysis disclosed significant variations in how different coffee cultivars respond to shade. Some coffee varieties showed no change in yield with shade, while others exhibited an inverted U-shaped response (highest yield at a specific shade level) or a continuous decrease with increasing shade. This research underlines the importance of considering the specific coffee cultivar when assessing its suitability for shade-grown coffee production within agroforestry systems. The authors also call for further research comparing coffee productivity across a wider range of low to moderate shade levels (10-40%) to potentially identify optimal shade levels for different coffee varieties.

3.1.2 Intercropping

Intercropping is a well-known crop diversification practice of growing two or more crops on the same field at the same time aiming at both overyielding effect (land use equivalent ratio > 1) and improved agrobiodiversity (Figure 3). A meta-analysis by Rodriguez et al. (2020) found that planting grain cereals alongside grain legumes boosts agricultural sustainability. This approach encourages plants to utilize more natural N sources, reducing the need for external fertilizers. However, the success of intercropping depends on the specific mix of crops and how scientists measure N fixation. The study uncovered that intercropping significantly increased the total N uptake by the soil compared to sole legume crops (by an average of 25%). Interestingly, there wasn't a major difference in N uptake between intercropped and sole cereal crops. The real benefit came for the cereals themselves – intercropping significantly boosted their N uptake compared to monocrop (by an average of 61%). The study also explored how the proportion of cereals and legumes in the intercropping system affected N fixation. Interestingly, when compared to sole legume crops, intercropped legumes fixed slightly more N overall (an average increase of 14%). However, when considering the total amount of N fixed per unit area, intercropping reduced fixation by about 15%. This is because intercrops typically have a lower proportion of legumes compared to sole legume crops. To account for this difference, researchers adjusted the data to reflect the actual number of legumes planted in each system highlighting the importance of considering the amount of legumes planted.

Another meta-analysis examined 69 different systems where grasses, cereals, and legumes were grown together (grass-grain legume intercrops) (Bybee-Finley et al., 2016). It was found that intercropping led to more consistent yields compared to growing these plants separately (sole crops). The results showed a clear advantage for intercropping, with coefficients of variation of 0.25 for grass monocultures, 0.30 for legume monocultures, and just 0.19 for intercrops.

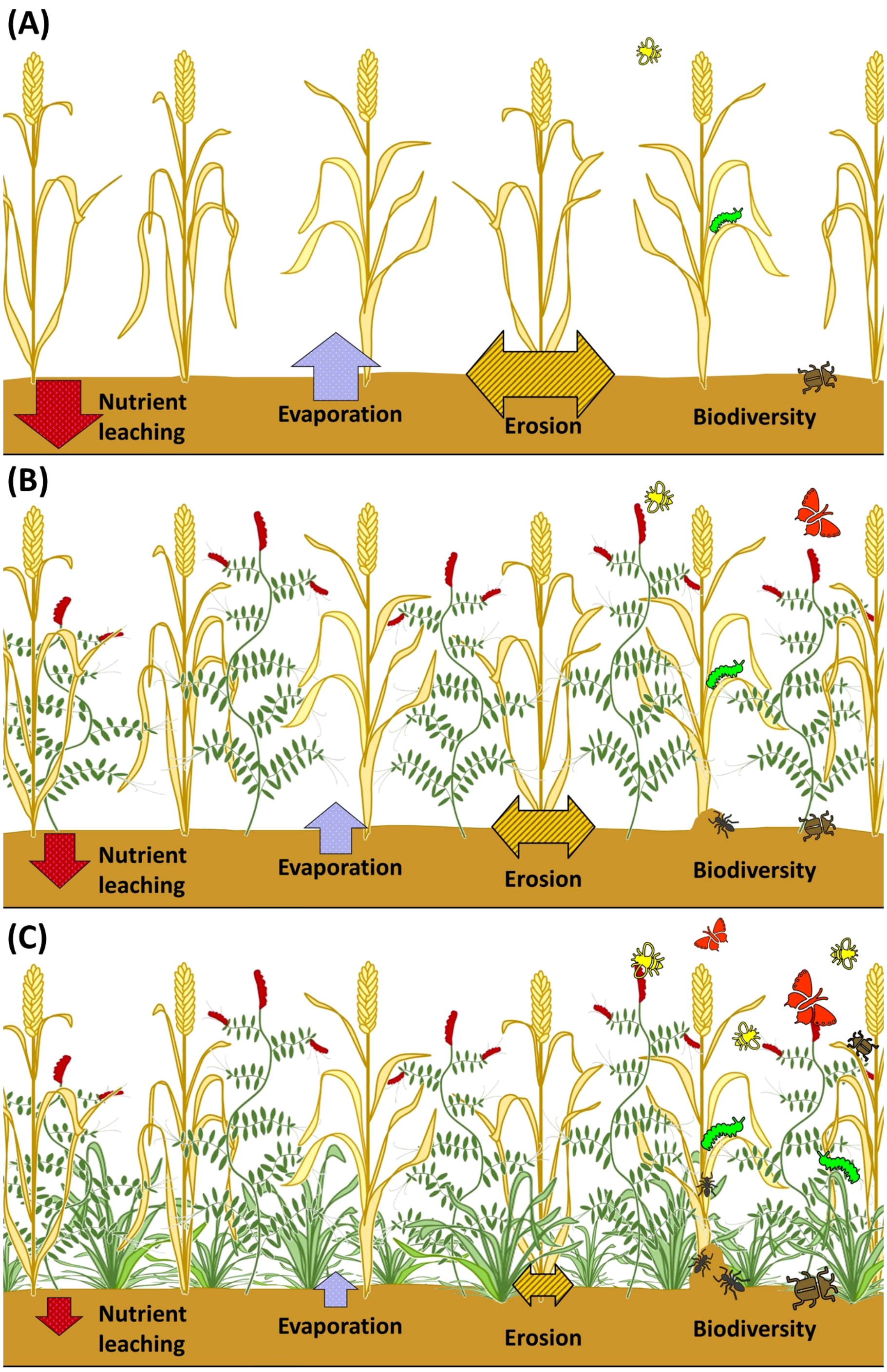


FIGURE 3
Schematic representation of an arable monoculture **(A)**, a simple intercropping of two plant species **(B)**, and an extended intercropping (mixed cropping) of more than two plant species **(C)**. The size of the arrows indicates changes in nutrient leaching, evaporation and erosion (arrow size) due to the increase in plant diversity-related soil cover and soil rooting. The insects' number and size schematically represent changes in habitat conditions for faunistic biodiversity.

Raseduzzaman and Jensen (2017) investigated 33 articles to assess the grain legume intercropping effect on cereal yield stability. They found that across major climatic zones (Tropical Zone, Subtropical Zone, and Temperate Zone), cereal-grain legume intercropping significantly increased the yield stability compared with respective sole cropping systems.

Furthermore, the meta-analysis by Verret et al. (2017) investigating the effects of intercropping on weed suppression in cash crops (e.g., corn, forage) included 34 articles and encompassed 476 experimental units. Each unit represented a unique combination of factors like site, year, cash crop type, legume companion species, and agricultural practices. The analysis showed that intercropping significantly reduced weed biomass by 56% compared to non-weeded monoculture control treatments.

The work of Bedoussac et al. (2015) investigated the effects of intercropping on grain yield, protein concentration, economic return, and resource utilization across 58 field experiments conducted in diverse European pedo-climatic conditions. The authors found that intercropping yielded higher and more stable grain yields compared to the average sole crop yield (0.33 kg m^{-2} vs 0.27 kg m^{-2}). In addition, intercropped cereals exhibited a higher and more stable protein concentration than sole cereals (11.1% vs 9.8%). Furthermore, intercropping resulted in a significant increase in gross margin compared to the average sole crop gross margin (702 € ha^{-1} vs 577 € ha^{-1}). Advantages in intercropping were observed due to likely better resource use, such as light interception efficiency and more balanced utilization of both soil mineral N and atmospheric N_2 fixation. Importantly, the overall advantages of intercropping were most pronounced in systems with low N availability. Similar findings were observed in an organic farming system in a semi-arid environment of southern Italy, where durum wheat and forage legumes produced higher grain yield and grain protein than durum wheat monocrop (Scordia et al., 2024).

3.1.3 Mixed varieties

Varietal mixing is an agricultural practice that consists of sowing a heterogeneous mixture of varieties of the same species in the same plot (Figure 4).

It has been reported that planting varietal mixtures leads to more stable yields, especially when faced with biophysical constraints such as droughts, erosion, poor nutrient contents, and heavy pest pressure or weed infestation (Von Cossel et al., 2019).

A meta-analysis examining over 3,600 observations from 91 studies (Reiss and Drinkwater, 2018) found a surprising benefit to planting multiple crop varieties together (intraspecific mixtures). These mixtures yielded 2.2% more on average compared to fields planted with a single variety (monoculture). This advantage was even greater under stressful conditions, like low nutrients or heavy pest pressure. The authors also revealed that planting variety mixes led to more stable yields over time, especially when faced with year-to-year weather variations.

Borg et al. (2018) conducted a comprehensive review of 32 research studies examining wheat mixtures in comparison to their individual components grown in pure stands. Their analysis demonstrated a notable increase in yield of 3.2% for each additional component variety when disease pressure was high. Overall, the average yield increase observed was 3.5%, with this figure climbing to 6.2% under conditions of elevated disease risk. These findings strongly suggest that cultivating mixed varieties of wheat holds significant promise for enhancing crop yields, particularly in agricultural settings that prioritize reduced pesticide use.

Worth to mention is the review of Hajjar et al. (2008), who found that increasing crop genetic diversity in arable systems could help increase pollination services and soil processes (carbon sequestration and soil erosion mitigation), contributing to the long-term stability of agroecosystems. Potential drawbacks or consequences along the values chain were identified, such as heterogeneous quality, practical and economic implications for processing (harvest and sorting the harvested material) among others.

3.1.4 Cover cropping

Cover crops, i.e., unharvested crops grown together or between primary cash crops, are used for multiple objectives, ultimately improving soil health and enhancing yields (Scavo et al., 2022). A meta-analysis by Garba et al. (2022) examined the influence of cover crops (Figure 5) on cash crop yield, soil water content, and soil mineral N in dryland environments. The analysis encompassed 1006 observations for cash crop yield, 539 observations for soil water content, and 516 observations for soil mineral N. The study identified

FIGURE 4
Example of a winter wheat (Triticum aestivum L.) population mixture in an organic farm located in Patti (Messina, Italy). The picture shows the different morphology of winter wheat inflorescences (photo courtesy of Aurora Maio, from the experimental farm of the University of Messina).

FIGURE 5
Example of a cover cropping approach in viticulture. The site is in Rodì Milici (Messina, Italy, 100 m a.s.l.). The grape variety is "Nero d'Avola", and the cover crop mix consists of *Vicia faba* var. Minor, *Trifolium alexandrinum*, *Hedysarum coronarium*, *Avena sativa*, x *Triticosecale*, and *Hordeum vulgare* (photo courtesy of Francesca Calderone, from the experimental farm of the University of Messina).

a minimum annual precipitation threshold of approximately 700 mm, acting as a "break-even point" for achieving significant yield benefits from cover crops compared to control fallows. Overall, cover cropping resulted in an average decrease of 7% in cash crop yield, 18% in soil water content, and 25% in soil mineral N. However, across climatic zones, soil types, and specific crop management practices, subsequent cash crop yields varied by +15%, +4%, -12%, and -11% in tropical, continental, dry, and temperate dryland climates, respectively. These findings highlight the importance of a thorough understanding of cover crop integration into cropping systems to minimize potential trade-offs between ecosystem services (e.g., soil health improvement) and disservices (e.g., reduced water availability for cash crops).

A meta-analysis by Jian et al. (2020) investigated the impact of cover crops on SOC, showing a significant increase (15.5% mean change) when cover crops were integrated into crop rotations. The mean rate of C sequestration attributable to cover cropping across all studies was 0.56 Mg ha^{-1} yr^{-1}. The largest SOC increase was found in shallow soil layers (≤30 cm), in fine-textured soils (39.5% mean change), followed by coarse-textured (11.4%) and medium-textured (10.3%). In temperate and tropical climates SOC raised by 18.7% and 7.2%, respectively. SOC further improved in cover crop mixtures than monoculture cover crops, and in legume cover crops than in grass species, and in species with higher biomass yield. Other soil quality parameters were enhanced, such as reduced runoff and erosion, and increased levels of mineralizable C, mineralizable N, and total soil N. Additional factors influencing SOC change were annual temperature, duration of cover crop implementation, geographic latitude, and initial SOC concentration.

The review of Kaye and Quemada (2017) highlighted that ecosystem services from using cover crops can synergistically promote services related to climate change. They found that soil carbon sequestration and reduced fertilizer use after legume cover crops can mitigate approximately 100–150 g CO_2e m^{-2} $year^{-1}$ of greenhouse gas fluxes, and the vegetation cover may mitigate 12 to 46 g CO_2e m^{-2} $year^{-1}$ of surface albedo change over a 100-year time horizon.

3.1.5 Crop rotation

Crop rotation is the practice of planting different crops sequentially on the same plot of land. The global metanalysis (11,768 yield observations from 462 field experiments) by Zhao et al. (2022) demonstrated that legume-based rotations have the potential to enhance crop production, especially when integrated into low-input and low-diversity agricultural systems (32%) than high-yielding environments (7%). Legumes, as pre-crops, consistently enhanced main crop yield (rice, wheat, maize) by 20% as compared to non-legume pre-crops across pedo-climatic regions.

John et al. (2021) found out that legume crop diversification in maize cropping, either in rotation system or intercropping groundnut, allowed for increased yield, protein, stability, and profits as compared to unfertilized and full fertilized maize monocrop across 29 farm sites (120 year-site combinations) in central Malawi (Africa). The legume diversification system performed best in marginal environments. The soil organic carbon was influenced by soil texture (sites with SOC >1.5% had sand content <50%) rather than the legume diversification system. Despite these positive results, authors drew attention to the need for agricultural policies that increase access of farmers to superior legume seeds and agroecology-based advice.

The multilevel regression analyses of Bowles et al. (2020), demonstrated that across a precipitation gradient in continental environmental zone of North America, more diverse rotations increased maize yields over time and across all growing conditions (28.1% on average). Even in drought years yield losses were reduced by 14.0%–89.9% under diverse rotation systems.

3.1.6 Mixed farming

Mixed farming involves crop-to-livestock integration on the same farm. Research by Pent (2020) analyzing 22 studies found that combining trees, pastures, and livestock in a single system (example see Figure 1), can significantly increase overall productivity. Compared to managing these elements separately, silvopastoral agroforestry practices can boost land output by 42-55%, depending on whether livestock production or forage yield is to be taken into account. Interestingly, this "overyielding" effect often occurs even when the individual production of trees, forage, or livestock goes down slightly within the silvopastoral agroforestry system. This suggests that the combined benefits outweigh any minor reductions in individual yields.

Jordon et al. (2022) carried out a meta-analysis with contradictory results on the overall sustainability of three selected agroecological practices (no-/reduced tillage, cover cropping, and ley-arable) in the temperate oceanic regions. The study found evidence (195 paired observations taken from 40 studies, most of them located in the UK, France, The Netherlands, Denmark, and Germany) for agroecological practices increasing the soil organic carbon but not the yield. They concluded that more research is needed on the question of how livestock can be best integrated to agroecological farming systems to create win-win opportunities for the farms, especially concerning the applications of ley-arable strategies. These recommendations are thus in line with those brought up by Snapp et al (Snapp et al., 2023).

Research by Falkowski et al. (2023), who collaborated with Maya farmers (milperos) in several communities in the Montes Azules Biosphere Reserve region in Chiapas (Mexico) highlighted a surprising fact: the dynamic polyculture system full of genetic resources produces charcoal that retains carbon at a rate 4 to 14 times higher than slash-and-burn systems reported elsewhere. While burning releases significant carbon (12.6 ± 3.6 t C ha^{-1} yr^{-1}), char production (3.0 ± 0.6 t C ha^{-1} yr^{-1}) and incomplete combustion help offset some of this loss. Interestingly, burning had minimal impact on soil composition, but it did significantly increase pH, potassium availability, and cation exchange capacity (by 2%, 100%, and 7%, respectively). This study suggests that Maya milpas, with their unique char production and management practices, have the potential to become long-term carbon sinks. However, this benefit hinges on the preservation of ecological knowledge within Maya communities. Socioeconomic changes and the potential for shortened fallow periods or land tenure insecurity could threaten this sustainable practice.

The review by Thornton and Herrero (2014), who discussed adaptation options available to smallholders in mixed crop–livestock systems in developing countries is worth mentioning. Among potential mitigation co-benefits, improving feeding through diet supplementation and improved grass and fodder species ranked highest in their analysis. However, high costs, labor demands, and lack of knowledge were identified as constraints to adoption. Other potential practices included the management of nutrients and soil, manure, grazing, and crop residues, with variable impacts on food security, resilience, and the promotion of diversification, along with managing risks (e.g., costs, competing demands, labor demand, limited access to information and technologies, lack of knowledge). They concluded that effective adaptation would require supportive policies, technical advancements, improved infrastructure, and better access to information, emphasizing that the development challenge remains significant and complex.

3.2 Soil management

To bolster the resilience of cropping systems, it is crucial to carefully consider the various tillage and amelioration practices that can be integrated into agroecological frameworks. These practices, when thoughtfully implemented, can significantly enhance soil health, improve water retention, and mitigate the adverse effects of climate change. Hence, the following section addresses specific tillage and amelioration techniques regarding their potential benefits and challenges for agroecological farming.

3.2.1 Tillage

Tillage, involving mechanical actions such as digging, stirring, and overturning, is the most common method used for soil preparation in agriculture. Conservation practices, such as reduced tillage, minimum tillage, and no-tillage, aim to preserve soil structure and health (Altieri et al., 2017) (Figure 6).

These practices focus on enhancing soil organic matter (SOM) by reducing soil degradation processes. A global study by Huang et al. (2018) examined the effects of no-till farming compared to conventional tillage. This analysis focused on greenhouse gas emissions (methane, carbon dioxide, and nitrous oxide), crop yields, and the overall impact on global warming for major cereal crops:

- Reduced methane emissions: No-till farming decreased methane emissions by an average of 15.5%.
- Increased nitrous oxide emissions: However, it also led to a 10.4% increase in nitrous oxide emissions, another greenhouse gas.
- Climate impact varies: The impact on crop yields depended on climate. No-till practices benefited yields in dry areas but hurt them in humid regions.
- Soil pH matters: On acidic soils, no-till reduced global warming potential without harming yields. Conversely, on alkaline soils, it increased yields without affecting global warming potential.
- Crops respond differently: Barley yields increased significantly (by 49%) with no-till, especially in dry climates. Rice fields also benefited, with a 22% reduction in both carbon dioxide and methane emissions. However, maize yields decreased.

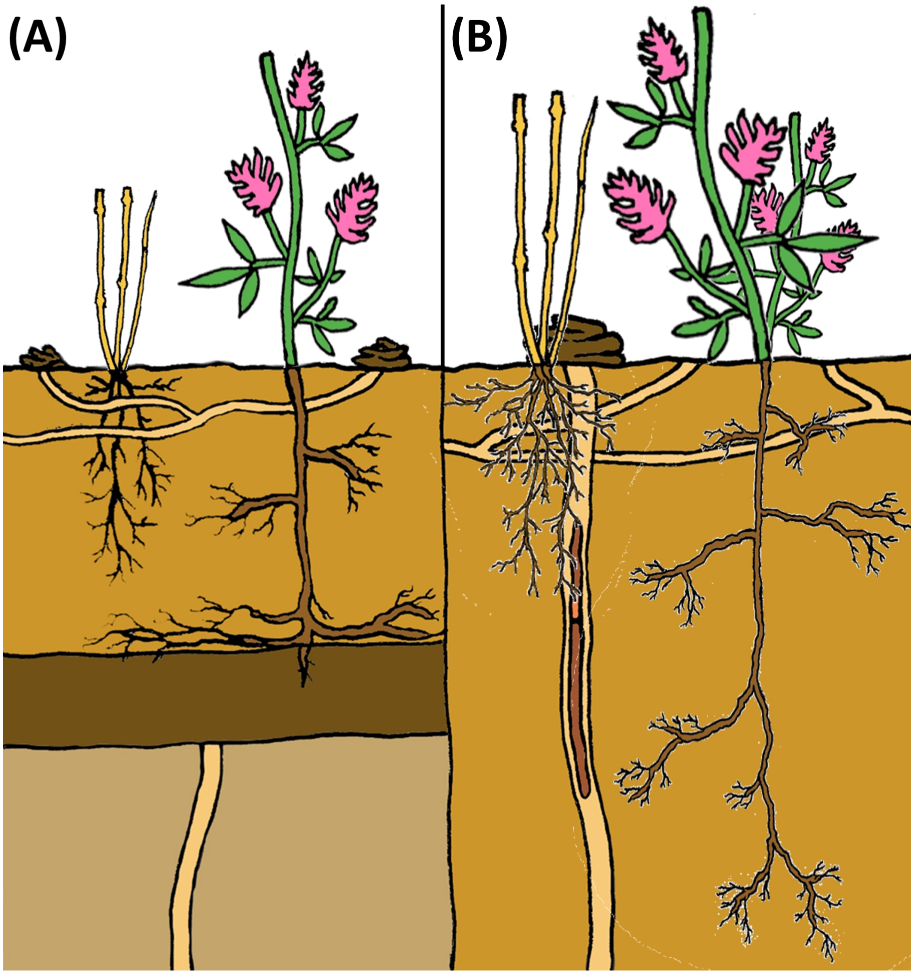


FIGURE 6
Schematic illustration of effects on the rooting zone of conventional tillage [**(A)**, indicating a compacted layer at ploughing depth of about 25 cm depth] and no-till management [**(B)**, indicating a higher earthworm activity and higher biomass growth and deeper rooting depth] (adapted from Hoeffner et al., 2022, and Pelosi et al., 2014). The brown soil casts on the soil surface represent the earthworms' excrement (small roll-shaped soil aggregates of clay-humus complexes), which are associated with mineral grains and plant remains and form a loose pile of smaller crumbs.

Overall, the effectiveness of no-till depends on several factors, including climate, soil characteristics, and crop type (Huang et al., 2018). Therefore, farmers need to consider their specific environment when choosing tillage practices. The authors also found that combining no-till with reduced N fertilizer rates can increase crop yields without worsening greenhouse gas emissions. Additionally, it was recommend exploring subsurface placement of N fertilizers in no-till systems to further reduce nitrous oxide emissions.

A long-term, 36-year study conducted in a temperate region examined the impact of crop rotation diversity and no-till cultivation on maize drought resilience. Surprisingly, the findings indicate that no-till practices did not influence the maize plants' ability to withstand drought conditions (Renwick et al., 2021). However, further analysis through path modeling confirmed a robust association between increased SOM and decreased water stress in maize plants, even though there were no measurable differences in SOM levels among the various crop rotations or tillage methods nor higher soil water retention, infiltration, or differential root water depth, suggesting that other mechanisms require investigations.

Lal (2020) also approved that increasing SOM content enhances plant-available water across all soil types (sandy, silty, and clayey textures) and can contribute to drought resilience by conserving water resources. As expected, the magnitude of this increase depends on site-specific inherent and external factors. This effect is attributed to a relatively greater increase in field capacity compared to the wilting point. Further research is needed to better understand the mechanisms and soil processes that lead to increased plant-available water content in relation to higher SOM levels.

3.2.2 Organic farming

Organic farming is aimed at avoiding or largely excluding (depending on the underlying certification requirements) the use of synthetic compounds, such as chemical fertilizers, pesticides, herbicides, growth regulators and livestock feed additives throughout agricultural practices. This common goal makes organic farming and agroecological farming similar, although agroecological practices are not necessarily applied in organic farming. Ponisio et al. (2015), meta-analyzed organic and conventional yields with more than 1000 observations. Overall, it was found that organic yields were only 19.2% lower than conventional yields, with different effects of crop types and management practices on the yield gap. The yield gap between organic and conventional monocultures was 17 ± 3% and increased to 21 ± 6% in organic and conventional polycultures. When organic and conventional did not include crop rotation, the yield gap was 16 ± 5%, while it increased to 20 ± 2% when both systems had a similar number of rotations. The most affected crops were root and tuber, with yield reduction of 30 ± 11%, followed by cereals (22 ± 3%), vegetables (17 ± 4%), legumes (15 ± 10%), oilseed (13 ± 5%), fruit and nuts (7 ± 5%). The authors underscored the importance of strategic investments in agroecological research as a means to enhance organic farming practices. Such investments, they suggested, could potentially bridge or entirely close the yield gap for certain crops or in specific geographic areas.

A rigorous assessment by Knapp and van der Heijden (2018) examined the year-to-year consistency of crop yields across three primary agricultural systems: organic farming, conservation agriculture, and conventional agriculture. The study, which drew on data from 193 studies and 2896 observations, accentuates that organic agriculture exhibits a notably lower degree of yield stability, with a 15% decline in consistency per unit of yield compared to conventional farming. While organic farming undoubtedly contributes to biodiversity and environmental sustainability, future research and development efforts should prioritize strategies to mitigate its inherent variability in crop yields. The authors suggest that incorporating green manure and optimizing fertilization practices could help narrow the gap in yield consistency between organic and conventional agriculture. Furthermore, the analysis uncovered that adopting no-till techniques within conservation agriculture does not significantly impact yield stability, as evidenced by its temporal stability of -3%, which is comparable to that of conventional tillage methods. This finding implies that transitioning to no-till farming does not compromise the consistency of crop yields.

3.2.3 Mulching

Mulching is a practical and affordable agricultural practice that can be readily implemented by farmers. This technique involves covering the soil surface with organic or inorganic materials to enhance soil structure, retain moisture, regulate soil temperature, and minimize nutrient loss, salinity, and erosion (Iqbal et al., 2020). The origin of the mulch material (on-farm or off-farm) strongly depends on the intended mulching effects (e.g., high or low albedo effect) and the local conditions (farming system, other farms in the region, seasonal straw yields/prices etc.) (Iqbal et al., 2020).

A thorough meta-analysis by Qin et al. (2015) investigated the effects of mulching on wheat and maize production, drawing on a vast dataset of 1310 yield observations from 74 studies conducted across 19 countries. The analysis indicated that mulching significantly enhanced yields, water use efficiency (WUE), and Nitrogen use efficiency (NUE) by up to 60% compared to non-mulched crops. These benefits were more pronounced in maize than in wheat and were more substantial when plastic mulch was used instead of straw mulch. Notably, plastic mulch proved more effective in relatively cool conditions, while straw mulch exhibited the opposite pattern. Additionally, the benefits of mulching tended to diminish as water availability increased. The positive effects of mulching were not influenced by the organic matter content of the soil. The authors concluded that mulching can play a crucial role in bridging the yield gap between potential and actual crop yields, particularly in arid regions and agricultural systems with limited nutrient inputs. However, the management of soil mulching requires site-specific knowledge.

Fraga and Santos (2018) conducted a modeling study to predict grape yields in the Alentejo wine region under the RCP8.5 climate change scenario over the next 60 years, comparing non-mulched and mulched vineyards (Southern Portugal). Authors found a general yield decline in grape yield due to warmed growing seasons, however, mulching can reduce the yield decreasing trend from −0.75% year^{-1} in non-mulching to −0.66% year^{-1}.

3.2.4 Green manure

Green manure is undecomposed organic material (green) that can be obtained either by growing short-term crops (cover crops including legumes) and incorporating them into the soil in the same place (*in-situ*) or by collecting green leaf residues (*ex-situ*) from nearby sources and integrating them into the soil a few days (15-30) before sowing the main crop (Meena et al., 2018).

An in-depth meta-analysis conducted by Ma et al. (2021) evidenced that the application of green manure in Northern China significantly enhanced soil health. Key benefits included a reduction in soil bulk density by approximately 5.6%, a 28% increase in microbial biomass carbon, and a 14-39% improvement in soil enzyme activity. Among various green manure types, legume-based green manure more effectively increased nitrate and hydrolyzable N levels, while non-legume green manure more notably elevated available potassium. Although green manure treatment led to a decrease in soil gravimetric water content, it consistently boosted maize yields by 11% on average. However, the impact of green manure on wheat and potato yields was less predictable. In conclusion, the strategic use of green manure in Northern China offers a promising avenue for improving soil quality and enhancing cash crop production. For example, a field study on several forage legumes in Maragheh (Iran), such as, among others, grasspea (*Lathyrus sativus*), maragheh vetch (*Vicia villosa*), berseem clover (*Trifolium alexandrinum*) and sanfoin (*Onobrychis sativa*) showed that across species, green manure had significant effects on SOC, calcium carbonate equivalent (CCE), bulk density, moisture percentage and electrical conductivity of soil extract (Habibi et al., 2013).

3.3 Holistic views on ecosystem services performance of agroecological farming

Jeanneret et al. (2021) explored the application of landscape ecology methods in agroecology, focusing on biodiversity conservation, regulating ecosystem services (pest control, pollination), agroforestry implementation, and agroecological innovations in a European context. Their mindset aligns with Altieri et al. (2015), and Morizet-Davis et al. (2023), emphasizing the crucial role of biodiversity in tackling future climate change challenges. In a thoroughly prepared review, Jeanneret et al. (2021) provide a wide range of relevant solutions and next steps to be taken toward a successful incorporation and upscaling of agroecological practices in European agricultural systems. The authors recommend that a better understanding of the potential benefits of traditional agroecological farming on ecosystem services requires a site-specific bottom-up assessment. This approach should tailor the evaluation to the unique conditions and challenges of each location. Further research and involvement of the farmer's experiences and ideas are seen as crucial to identifying optimal combinations and scaling strategies for agroecological practices at the landscape level, maximizing their support for biodiversity and other ecosystem services.

Cadel et al. (2023) investigated the effects of maximizing ecosystem services (bundles) through agroecological practices on agricultural productivity. Since there are no significant effects of soil-based ecosystem services on agricultural production, it is possible to adopt agroecological practices without compromising the economic performance of the agricultural system, argued the authors. Key agroecological practices are (i) the implementation of wide and diverse rotations, (ii) the targeted use of cover crops, (iii) a reduction of tillage intensity, and (iv) a sound recycling of organic material by the application of organic fertilizers. According to Cadel et al. (2023), a more comprehensive review of further literature is recommended since only 40 documents are included in this meta-analysis. For instance, South America, Russia, and Africa are not covered by this study, indicating, but not proving, a potential lack of information on agroecological approaches in those regions. As a solution, authors suggest widening the view on literature by excluding search terms like "ecosystem services".

Snapp et al. (2023) carried out a meta-analysis of 138 scientific articles selected from a total of about 30,000 articles, as well as several interviews with organizations. With climate change adaptation in focus, Snapp et al. found significant evidence for agroecological practices associated with farm diversification along with the co-creation of knowledge being most helpful in low- and middle-income countries to better cope with the ongoing climate crisis. Especially, wide crop rotations and the application of cover cropping strategies provide numerous positive impacts in terms of crop yield, pollination, pest control, nutrient cycling, water regulation and soil fertility. In contrast, there was only modest evidence for the potential climate impact of agroecological practices themselves. It was only found that agroforestry in the tropical zone could have a positive impact by sequestering atmospheric carbon in the soil. Hence, it was recommended to gather more information on the potential greenhouse gas emissions through the application of agroecological practices. Further, according to Snapp et al., more data is required about livestock integration into agroecological farming systems, as well as the resilience of agroecological farming systems to extreme events.

An analysis of 15 case studies explored the impact of agroecology on food security and nutrition across four key areas: crop diversity, mixed farming with livestock, soil management, and socioeconomics (Bezner Kerr et al., 2021). Encouragingly, 13 out of the 15 cases showed positive outcomes, and it was shown that the combination of different agroecological practices, and especially also social innovations, increased the effect. While Bezner Kerr et al. (2021) provide strong evidence for the benefits of agroecology, the researchers acknowledge the need for more rigorous research designs. This includes methods like case-control studies and longitudinal studies, which can better isolate the impact of agroecology from other factors that influence food security and nutrition. Additionally, the study highlights the need for more research on the social and economic aspects of agroecology. This could include examining the role of direct marketing, addressing social inequalities, and improving land and natural resource governance.

Research by Himmelstein et al. (2017) across Africa found that intercropping boosted crop yields by an average of 23% and increased farmer income by $172 per hectare. However, the effectiveness of intercropping varied depending on how it was managed and the local environment. Interestingly, the authors did not find a clear benefit from using legumes, reduced tillage, pesticides, or fertilizers in conjunction with intercropping. Additionally, while integrated pest management (IPM) alone increased yields by 20%, combining IPM with intercropping resulted in lower yields (24% less) than IPM alone. These findings suggest that intercropping is a promising approach for sustainable agriculture in Africa, but it's crucial to consider other factors for optimal results. One key factor is controlling weeds that compete with crops. The study highlights the need for further research to explore how intercropping interacts with other sustainable practices in different environmental and economic settings. This will help to refine intercropping techniques and maximize its benefits for African farmers.

A meta-analysis by Morugán-Coronado et al. (2020) investigated the effectiveness of several sustainable farming practices as alternatives to conventional monoculture systems. The study examined 187 experiments from 46 scientific publications. These sustainable practices included planting a variety of crops together (crop diversification), minimizing soil disturbance (conservation tillage), and using organic fertilizers. All these practices increased the amount of SOC. Notably, the most significant increase in SOC was observed with the integration of permanent alley cropping systems. Soil N levels followed a similar pattern to soil organic carbon (SOC), although no-tillage did not significantly affect N levels compared to conventional tillage. While soil phosphorus (P) content remained relatively unchanged, permanent alley cropping had a negative impact on P levels. Surprisingly, the presence of alley crops, conservation tillage practices, or organic fertilization did not significantly influence tree crop yields. However, annual crop yields were more sensitive to regional climatic conditions, potentially declining in warm and dry areas. In conclusion, the integrated implementation of intercropping, conservation tillage, and organic fertilization effectively enhanced soil quality and fertility, while providing year-round ground cover to safeguard the soil. Morugán-Coronado et al. (2020) therefore suggested prioritizing annual alley cropping with minimum tillage over permanent crops with no-tillage, particularly in warm and dry regions, to mitigate potential negative effects on soil P and N availability. Furthermore, it was indicated that the assessed soil properties may not be the primary drivers of long-term variability in crop yield.

3.4 Isolated views and experimental approaches of applying agroecological practices

Lu et al. (2022) focused on the agroecological practices 'conservation tillage' and 'cover crops', in a meta-analysis based on about 30 studies from the US using a sign test approach by Bushman and Wang (2009). This systematic analysis identified several key factors influencing farmers' decisions to adopt these agroecological practices, including their willingness to seek and utilize information, the size and vulnerability of their landholdings, and higher levels of income and formal education. However, this study does not specifically consider the agroecological farming concept which omits the contextualization of agroecological practices employed. Additionally, the study omits recommendations for further research on how these agroecological practices contribute to enhanced farm resilience. Further, given the absence of an agroecological focus in the study by Lu et al. (2022), replicating the investigation of driving factors for implementing more resilient agroecological practices in relation to farmer perceptions within agroecological contexts could be a valuable future research direction.

Christel et al. (2021) screened 100 scientific documents in search of evidence on the influence of entire farming concepts (conventional, organic, biodynamic) on the ecological quality of the soil. Literature was analyzed with a view on the respective sum of the cultivation concept-typical farming practices – not the individual practices. The term "resilience" is not mentioned directly, but it can be assumed that it is considered implicit in the biological functioning of the soil. Not surprisingly, the literature also shows that organic and biodynamic cultivation concepts have far more positive effects on the ecological quality of the soil than the conventional cultivation concept. It was also shown that large parts of Africa, and Eurasia are underrepresented in the number of scientific studies on the topic compared with the Americas. Following Christel et al. (2021) it can be recommended that organic fertilization and longer crop rotations are the most favorable practices to improve organic soil quality, and more studies on the influence of soil-conserving agricultural practices on the soil fauna are needed.

Regarding biological plant protection, a meta-analysis by Tonhasca and Byrne (1994) examined 21 studies on agroecosystems with diversified cropping systems. The analysis established that these diversified systems when compared to simpler control systems, harbored moderately lower populations of herbivorous insects. This can help reduce the need for artificial interventions in the agroecosystem, which can enable more environmentally friendly cultivation of the plants compared to large-scale cultivation.

Another meta-analysis of 43 studies also found evidence that increased habitat diversity, such as more finely structured agricultural landscapes with wide crop rotations and the use of cover crops, leads to a greater supply of biocontrol agents (predators), which can reduce the need for plant protection measures (Langellotto and Denno, 2004).

4 Conclusions

Taken together, the meta-analyses reviewed in this study highlight the complex interplay among soil, plant, climate, management, and socio-economic context within the selected agroecological practices and their potential effects on the resilience of farming systems. Positive, null, or negative effects were identified in the different studies, which largely depended on the factors mentioned above.

In the agroforestry practice, common recommendations were the need for further research on (i) the overall benefit agroforestry can provide for more resilient farming systems at the field and landscape level, (ii) other companion planting options and designs, (iii) tree traits and diversity, (iv) crop varieties with tolerance to shade, along with (v) long-term monitoring to assess the whole lifespan of these systems. Careful consideration of these factors is essential to optimize crop yields and maximize the overall benefits of integrating trees into agricultural landscapes. In the best case, agroforestry can serve as a key measure in agroecological farming to increase the resilience of the system, for example by improving (i) erosion control potential, which helps to reduce soil degradation potential, (ii) habitat functioning, which helps to counteract the loss of biodiversity in agroecosystems, and (iii) response diversity, which improves the ability of the agroecosystem to recover from disturbances such as drought, flooding or pest infestation.

Less prominent but still important, cover crops in crop rotations can also strengthen the resilience of the farming system by increasing the soil's organic carbon content and improving several soil chemical parameters. Furthermore, they increase the potential of the cropping system to act as a sink for atmospheric CO_2. However, this is a long-term process (approx. 150 years until saturation) (Poeplau and Don, 2015), the extent of which varies considerably depending on the climate and available water content of the soil, soil type, type of cover crop and duration, biomass yield and C/N ratio, as well as the initial SOC concentration.

Also, the net effect of no-till, relative to conventional tillage, was influenced by several environmental and agronomic factors (climatic conditions, tillage duration, soil texture, pH, crop species), which further emphasizes careful planning and improved knowledge of the interaction among crop, site-specific conditions, and management.

Intercropping integrated with pest management penalized crop yield more than the system alone, suggesting that effective implementation of intercropping would depend on considering adequate control of competing vegetation. On the contrary, other studies proved that intercropping significantly reduced weed biomass, stabilized crop yield over time, and increased grain protein concentration and farm gross margin, with larger advantages under low levels of soil N availability and marginal settings, and in systems were the use of synthetic products are largely avoided.

Studies have shown that including legumes in agricultural systems, either as cover crops or intercropped with other plants or in rotation, can be a sustainable practice. Legumes make it possible to use more natural sources of N in agroecosystems, thus reducing the need for external fertilizers. Planting a variety of crop genotypes together (varietal mixtures) helps stabilize yields, especially under abiotic (droughts) and biotic stresses (heavy pest pressure or weed infestation) or poor nutrient soils. In the long-term, this helps improving the resilience via increased soil fertility which allows for a higher response diversity within the soil fauna.

Mulching is a promising agroecological practice to increase crop yields, WUE, and NUE, however, the management of soil mulching requires site-specific knowledge. Green manure generally improves soil quality, nonetheless, results on some crops (i.e., wheat and potato) were inconsistent as compared to others, like maize.

To ensure or even improve the long-term resilience of farming systems in the face of worsening climate change impacts, increased investment in agroecological research is crucial. This research should focus on four key areas:

- Bridging the yield gap: Organic management practices need improvements to close the yield gap between organic and conventional agriculture.
- Livestock integration: Research on effectively integrating livestock into agroecological systems (e.g., silvopastoral agroforestry) would be a useful step in creating win-win scenarios for farms, boosting both productivity and resilience.
- Complex multi-trophic systems: Developing and understanding more complex systems that integrate plants and animals across multiple trophic levels (feeding relationships) is essential. These systems can promote nutrient cycling and align with the principles of a circular economy, where resources are reused and waste is minimized (Lewandowski et al., 2024).
- Optimal agricultural and food policy conditions and regulations: Farmers are already confronted with a great deal of red tape in many places. It is therefore necessary to support farmers at the local level in integrating agroecological practices through a legal framework that is both worthwhile and easy to implement.

In conclusion, enhancing biodiversity at the field level, including macro-, meso-, and microflora and -fauna, through targeted agronomic practices to enhance crop diversification and ecological soil management has proven essential in the short term for driving the transition toward more agroecological and resilient farming systems. By fostering diverse biological interactions, these practices improve soil health, crop yield and stability, nutrient cycling, pest regulation, and overall ecosystem stability. This approach not only enhances immediate agricultural sustainability but also lays the foundation for long-term resilience to climate variability and environmental pressures.

Author contributions

MC: Conceptualization, Investigation, Methodology, Visualization, Writing – review & editing, Funding acquisition, Supervision, Writing – original draft. DS: Conceptualization, Investigation, Methodology, Visualization, Writing – review & editing, Writing - original draft, Funding acquisition, Supervision. MA: Investigation, Writing – review & editing. FG: Conceptualization, Funding acquisition, Investigation, Methodology, Supervision, Writing – review & editing.

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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

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