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The ecological and socioeconomic sustainability of organic agroforestry: a systematic review

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Abstract Organic agriculture and agroforestry are two agroecological approaches that have been proposed to address the many negative externalities of intensive agriculture.However, their comparative efficiency in promoting sustainability when combined is unclear, as they are typically studied in isolation. To address this we conducted a systematic review of comparative studies addressing organic versus conventional agroforestry and their monocultural counterparts. We conducted a content analysis resulting in an impact matrix utilizing seven broad categories encompassing ecological, socioeconomic and environmental aspects of sustainability. By analyzing these impact categories separately, it is possible to highlight the distinct advantages and issues in organic agroforestry systems over alternative systems, as well as the potential for multifunctionality. Research in organic agroforestry is strongly biased towards South American Cocoa and Coffee, but, in spite of this, evidence thus far suggests that organic agroforestry has many advantages across all categories studied and few drawbacks; the main one being yield of single crops. A large number of comparisons yielded neutral outcomes, suggesting that there are a limited set of trade-offs associated with organic agroforestry, many of which may be attenuated by altering management and market conditions. We conclude by highlighting key research areas in organic agroforestry which need to be addressed including: the differing ways of quantifying yield, staple crops and expanding the geographic range of studies.

Keywords Agroecology · Crop diversification · Organic farming · Multifunctionality

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Introduction

The market for organic certified products as well as the area of agricultural land under organic cultivation is growing (Willer et al. 2023). This is predominantly

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driven by consumer recognition of the environmental and health issues associated with conventional production (Katt and Meixner 2020), and by the worldwide national policies promoting organic agriculture (Willer et al. 2023). Purchasing organic certified goods is one of the few options consumers have to consume in a more sustainable manner and attempt to reduce their individual impact on the environment in a bottom-up, market driven approach (Massey et al. 2018). However, the environmental benefits of organic agriculture are contested in the literature (Tscharntke et al. 2021).

While many studies and meta-analyses have confirmed an array of ecological and environmental benefits conferred by organic agriculture (Smith et al. 2019b; Stein-Bachinger et al. 2021), this often incurs yield reductions averaging 20% (Gong et al. 2022; Smith et al. 2019b). Given this trade-off, in recent years, questions have been raised as to whether alternative agroecological practices may have better outcomes with less drawbacks and yield losses. For example, Tscharntke et al. (2021) showed that organic agriculture is less effective at preserving biodiversity than other practices aimed at improving agricultural diversity, such as crop diversification and incorporating semi-natural habitat structures. Clark and Tilman (2017) demonstrated that organic farms require more land for equivalent yields, which is claimed to offset conservation benefits if more land is converted to agriculture. They also illustrated that in paired organic and conventional farms, organic farms have higher eutrophication and acidification potential and equivalent greenhouse gas emissions. Meanwhile, Smith et al. (2019a) demonstrated that in spite of enhanced soil carbon sequestration, the need for more land for equivalent yields means organic agriculture may result in worse emissions than conventional. This indicates that it may be prudent to integrate additional agroecological practices in organic agriculture rather than emulating conventional systems, therefore ensuring that the environmental benefits live up to consumer expectations (Rosati et al. 2021).

Agroforestry is one such agroecological practice which, if integrated into organic agriculture on a wider scale, is a promising option to improve the sustainability of both organic and conventional agriculture. In comparisons to monocultural systems, agroforestry has been repeatedly shown to increase biodiversity, sequester higher amounts of carbon, reduce nutrient leaching and generally provide a wide array of ecosystem services (Jose et al. 2009; Torralba et al. 2016; Santos et al. 2019). System yields and calorie output per hectare can also be higher in agroforestry systems (Pérez-Neira et al. 2023). Thus, organic agroforestry may be a way to offset some of the issues facing “standard” organic agriculture and back-up the perceived improvements to system sustainability.

Rosati et al. (2021) published a narrative review on how agroforestry can have transformative potential for integration in organic agriculture, potentially allowing for ecological intensification rather than simple input substitution. Based on research in organic farming and agroforestry separately, they hypothesize a number of synergies, ameliorations and drawbacks. However, Rosati et al. (2021) emphasizes that there are very few comparative studies addressing organic agroforestry and highlight the need for more research. Even in the short time since their work was published, the field has progressed to further address this gap and we believe it is pertinent to highlight the current body of evidence concerning the utilization of agroforestry in organic farming via a systematic review. We compare organic agroforestry systems to their conventional and monocultural counterparts in terms of broad categories encompassing ecological, socioeconomic and environmental aspects of sustainability. In doing so we aim to provide a checkpoint for research in organic agroforestry thus enabling the scientific community to better address knowledge gaps and provide insight into the hypothesized benefits and drawbacks.

Methods

The search for papers included in our review was conducted using Scopus on the 21st of November, 2023 using the search term (agroforest* OR silvopast* OR silvoarable OR "alley cropping" OR "forest farming") AND ("organic agriculture" OR "organic farming") OR “organic agroforest*”. Using "organic agriculture" and "organic farming" rather than simply "organic" may have limited the number of relevant results but, using "organic" resulted in an excessive number of studies discussing only organic matter. Nonetheless, the search term still produced 208 results.

Requirements for inclusion were as follows:

1. The study must include organic agroforestry (OA, either certified or as declared by the authors) and one or more comparison systems; these being conventional agroforestry (CA, including among others the use of synthetic pesticides and industrial fertilizer), organic monocultures (OM, crops in sole or rotational cropping systems, either certified or as declared by the authors) and conventional monocultures (CM, sole or rotational cropping systems, with the use of synthetic pesticides and/or industrial fertilizer). (Note that a few studies rather used high or low management intensity in conventional and organic systems, but this mostly corresponded with the organic/conventional monocultural vs. agroforestry systems used by the majority of included studies).
2. The systems for comparison must cultivate the same primary crops as that of the organic agroforestry system.
3. Differences between systems must be assessed via significance tests, not just descriptive statistics.

Forty-five studies met the inclusion criteria, a list of which can be found in Supplement 1 (S1). The content of each paper was evaluated and the main findings were extracted from the figures and tables of and summarized in directional comparisons to organic agroforestry only, in S1. The extracted findings either refer to the entirety of the farm(s)/system(s) studied or to a given area in each system (e.g. 1ha) unless specifically stated otherwise. Comparisons can be: *Positive,* meaning the variable was significantly higher or lower in organic agroforestry reflecting a beneficial outcome (e.g.significantly higher yield or less emissions), *Neutral*, meaning there was no significant difference between the systems, *Negative*, meaning the outcome in organic agroforestry was significantly worse than in the comparison system, and *Conflicting*, meaning multiple studies showed both positive and negative outcomes for the same variable (e.g. one study shows that organic agroforestry has higher soil nitrogen concentrations while another has significantly lower values).

All key findings were included and categorized into one of seven broad categories to aid organization and discussion. The categories are: biodiversity; socioeconomic factors; yield; greenhouse gasses and energy use; pollution, water and abiotic impacts; pests, disease and weeds; soil physicochemical properties, nutrients and fluxes.

The results in S1 are summarized by category in Fig. 1. To aid in the visual assessment of the results, strip plots for each category were made for each comparison (Fig. 2). Each comparison outcome was given a score, 10 being Positive, 7 for Positive/Neutral outcomes, 5 for Neutral or Conflicting, and 1 for a Negative outcome. The mean thus visually represents the weight of evidence for each system comparison, such that higher weights suggest that organic agroforestry effectuates more positive outcomes and lower weights favor the alternative system. Note that yield was omitted from this figure due to the limited number of comparisons available and that the figure is meant solely for visual rather than numerical comparison.

Results

Geographic distribution and studied crops

Published research in organic agroforestry is strongly biased towards South America, with 31 of the 45 studies having been implemented there (Fig. 3). Costa Rica and Bolivia were also dominant within South America with 11 and 13 studies, respectively. The majority of research from Bolivia came from one cocoa cooperative and often one experimental site, though sometimes including farms in the surrounding region. This represents the most comprehensive across-system comparison made within the field of organic agroforestry. However, as this is one study site, with a focus on cocoa, findings from it cannot be generalized. Europe had the second highest representation with seven studies, but was limited to Spain and France. Africa, Asia and North America were limited in representation with four, two and two studies, respectively.

Nonetheless, comparative research in organic agroforestry has been increasing over time, beginning in 2006 with one study and peaking in 2021 with nine studies.

Cocoa and coffee were by far the most studied crops with 19 and 13 studies respectively (given a total of 45 studies; Figure 4). Grains were the primary crop in six cases, either being cultivated with trees

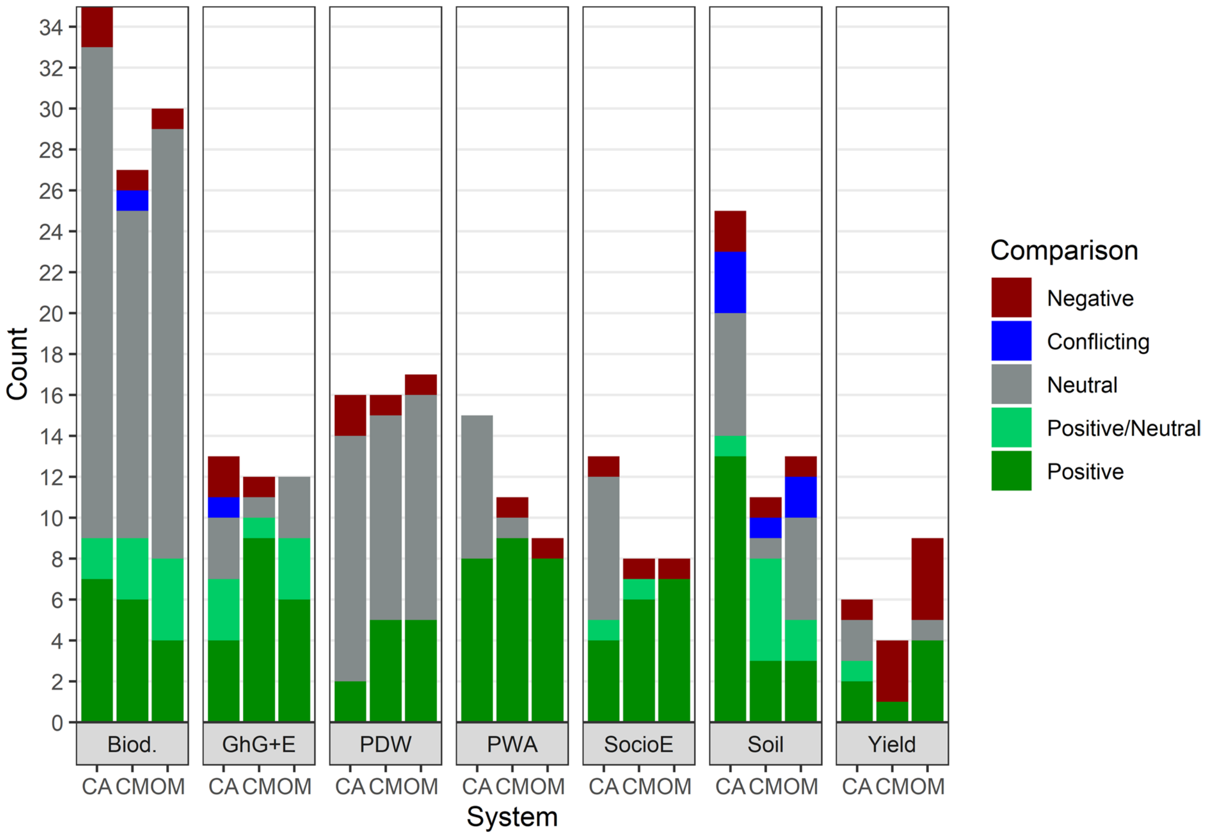


Fig. 1 Count of comparison outcomes in respect to organic agroforestry for individual variables across systems (CA: conventional agroforestry, CM: conventional monoculture, OM: organic monoculture) and categories. Positive means that organic agroforestry had a significantly better outcome compared to the alternative system and so on. Category abbreviations in order with the number of studies from which variables were extracted are: biodiversity(15); greenhouse gasses and energy(18); pests, disease and weeds(5); pollution, water and abiotic impacts(4); socioeconomic factors(8); soil (10); yield (13). made in R (R Core Team 2024) with ggplot2 (Wickham 2016)

to boost fertility or for other benefits such as erosion control. Silvopastoral systems accounted for three studies, vegetables for two, and fruits as a primary crop were only the case for one study on olives and another on pomegranate, although fruit was often a secondary crop in tropical systems. A notable absence is any study including nut or oil production.

Secondary crops and goods -defined as species cultivated in addition to the crop of primary economic or subsistence interest- were diverse but were mostly mixed fruits, particularly *Musa* spp., local timber and fuelwood species, and the occasional vegetable or understory legume. In studies that used and/or reported on nitrogen fixing trees two genera dominated, namely *Erythrina* spp. and *Inga* spp. However, this is due to the common use of these species in South American agroforests and the high proportion of literature from this region.

Biodiversity

Biodiversity was measured for the following taxa: trees, crops, understory plants, butterflies, ants, bees, earthworms, nematodes, various soil microarthropods, as well as a few studies addressing soil microbes. Neutral outcomes dominated this category, especially in studies addressing soil biodiversity. Nevertheless, limited negative comparisons meant the weight of evidence was still towards the positive with little difference between the systems compared (Fig. 2). The majority of outcomes relating to microbial communities did not differ between systems;

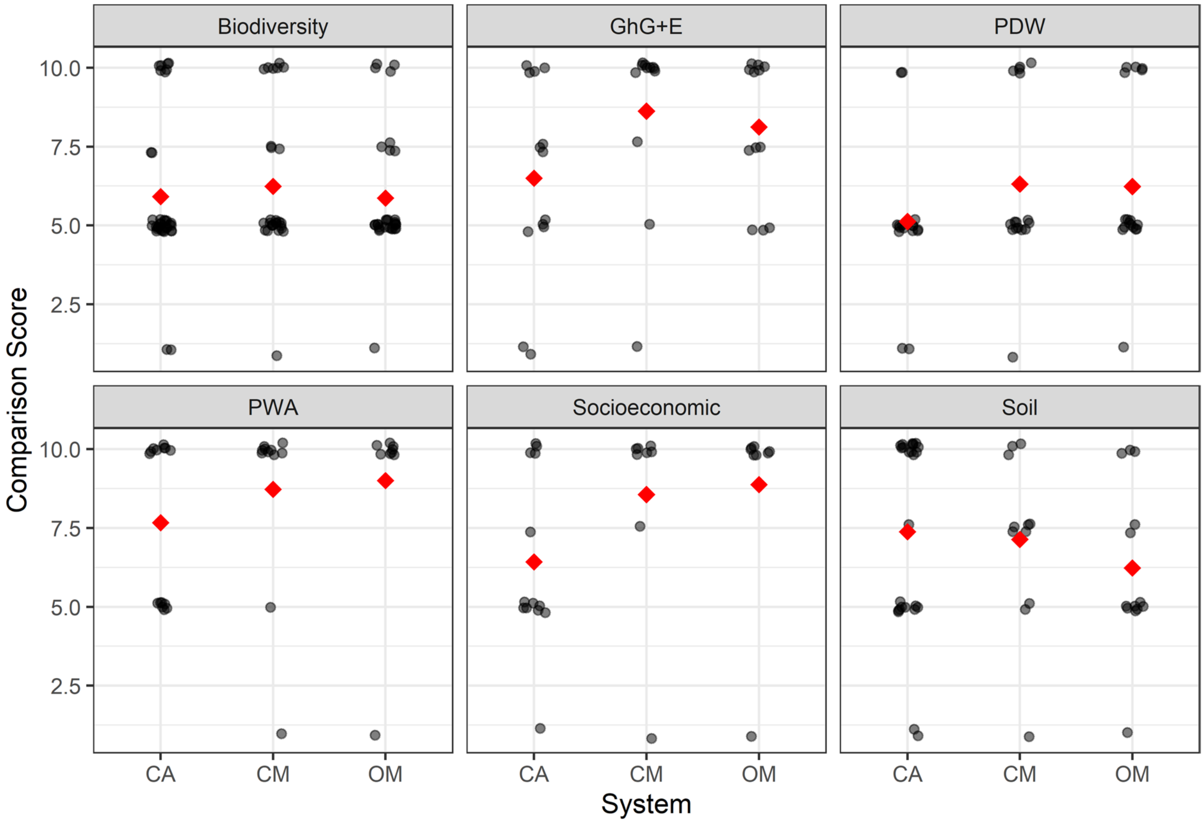


Fig. 2 Strip plots for outcome scores with mean in red (CA: conventional agroforestry, CM: conventional monoculture, OM: organic monoculture). Each comparison outcome was given a score, 10 being positive, 7 for positive/neutral outcomes, 5 for neutral or conflicting, and 1 for a negative outcome. neutral/negative outcomes did not occur. The mean thus visually represents the weight of evidence for each system comparison, such that higher weights suggest that organic agroforestry effectuates more positive outcomes and lower weights favor the alternative system. Note that yield was omitted from this figure due to the limited number of comparisons available and that the figure is meant solely for visual rather than numerical comparison. Category abbreviations in order of appearance are: greenhouse gasses and energy; pests, disease and weeds; pollution, water and abiotic Impacts. Made in R (R Core Team 2024) with ggplot2 (Wickham 2016)

rather each system had a unique community (Lori et al. 2022). Aside from higher butterfly abundance and diversity (Shannon's index (SI); Campera et al. 2021), above ground arthropod diversity tended not to differ between organic agroforestry and alternatives, while belowground arthropod diversity had mixed positive and neutral comparisons depending on the system and shade tree composition (Sauvadet et al. 2019). Notably nematode density was almost four times higher in organic agroforestry compared to conventional under two different shade tree systems and nematode diversity (SI) was doubled or more depending on the shade tree (Sauvadet et al. 2019). Organic agroforestry had very few negative comparisons in this category, with one especially notable one being less mycorrhizal fungi root colonization in coffee (Diaz-Ariza et al. 2021).

Socioeconomic Factors

In this category, in comparisons with conventional agroforestry the majority of factors were positive or neutral, with one -labor time- being negative (i.e. more labor hours required; Armengot et al. 2016; Fig. 1). This was also the only negative variable in comparisons with organic monocultures and conventional monocultures, with everything else being mostly positive (Fig. 2). Labor productivity and people fed per hectare were both more than doubled in agroforestry systems (Pérez-Neira et al. 2023),

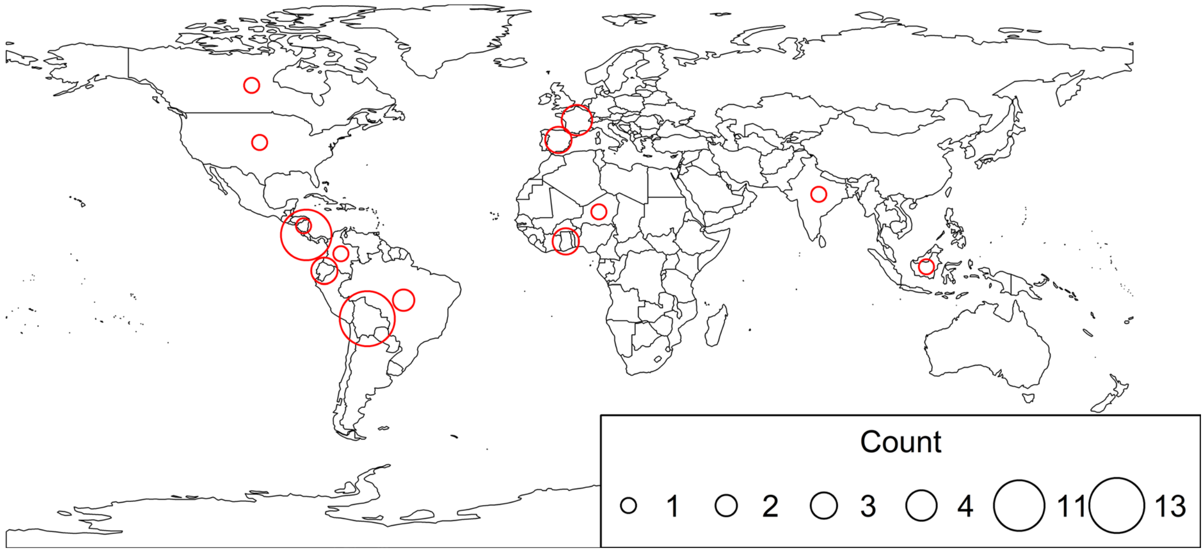
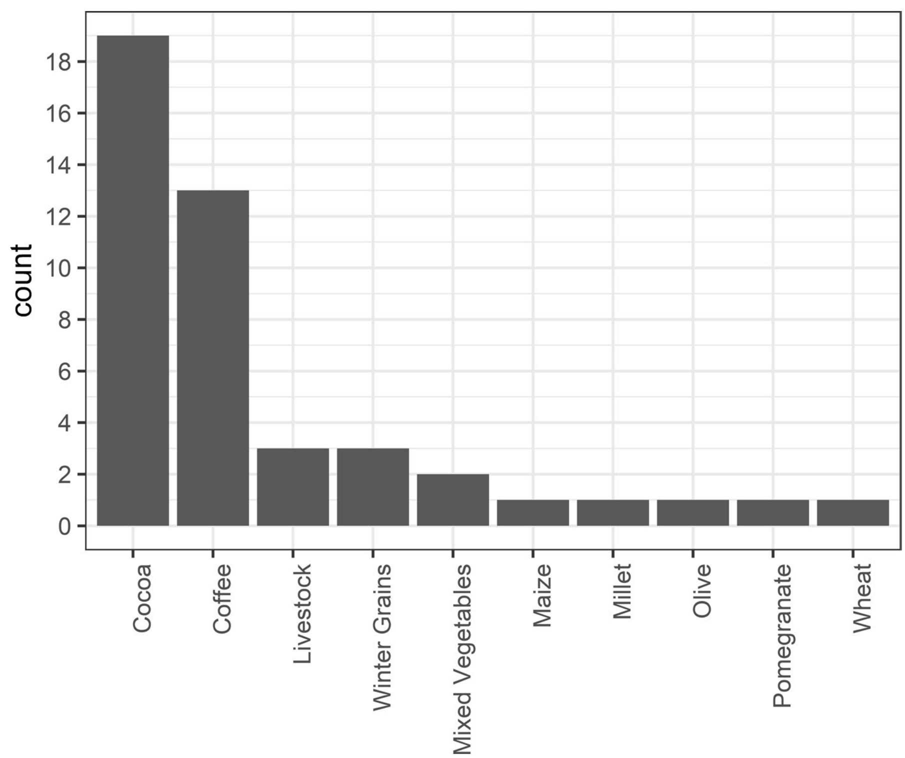


Fig. 3 Count of studies included per country proportional to circle size (legend corresponds to actual counts). Made in R (R Core Team 2024) with package rworldmap v1.3–8 (South 2011)

Fig. 4 Count of primary crops studied in organic agroforestry. Made in R (R Core Team 2024) with ggplot2 (Wickham 2016)



and gross margins incorporating additional labor costs were still 51% higher in agroforestry systems compared to monocultures (Armengot et al. 2016).

Profit was assessed in four studies and was generally higher in organic agroforestry except in comparisons with conventional monocultures which were mostly neutral, the exception being on a system in poor soil that was amended by organic agroforestry (Jacobsen et al. 2010). All other variables associated with economic wellbeing were generally positive.

Only one study addressed social resilience indicators which were generally higher for organic agroforestry systems in comparison for conventional systems (Jacobi et al. 2015). Although this study did not differentiate between organic monocultures and organic agroforestry systems, 28 out of 30 organic farmers included in the study, practiced agroforestry in their farms. The social resilience indicators included in this study were self-organization and adaptive capacity. Self-organization was further subdivided and measured as degree of connectedness and self-reliance, and adaptive capacity was measured as learning capacity and feedback mechanisms. Organic farmers had greater capacity to make connections and collaborate with other farmers. Although, the degree of self-reliance did not differ between organic and conventional farmers. Adaptive capacity indicators for both learning capacity and feedback mechanisms were higher for organic farmers. Organic farmers overall attended more training courses and had higher access to information sources and knowledge exchange platforms.

Yield

Yield outcomes were only available for cocoa (*Theobroma cacao*), banana (*Musa* spp.), pomegranate (*Punica granatum*), maize (*Zea mays*), coffee (*Coffea spp.*), olive (*Olea europaea*) and wheat (*Triticum aestivum*), and only coffee and cocoa had more than one study. Three studies assessed whole system yield (S1),that is the composite yield of all crops and products per unit land area, and one assessed land equivalent ratios (LER; Panozzo et al. 2020a). Aside from these four studies, yield comparisons are only made between primary crops.Most comparisons with conventional agroforestry were positive and neutral, with only coffee yield being lower (Figure I). Comparisons with organic monocultures gave more conflicting results with an equal number of positive and negative outcomes, while the majority were negative in comparison to conventional monocultures with only total system yield being higher in organic agroforestry. System yields and land equivalent ratios were generally higher in agroforestry systems while yields for individual crops were higher in monocultures. Only Panozzo et al. (2020b) considered crop quality, finding that wheat grown in organic agroforestry had a higher protein content than that grown in organic monocultures.

Greenhouse gasses and energy use

Overall, the majority of comparisons in this category were positive, though this was more often the case when comparing to the monocultural systems (Figs. 1, 2). Emissions per hectare (CO_2 equivalent) in organic agroforestry were higher than in conventional agroforestry (i.e. negative comparison; Pérez-Neira et al. 2020). The same study found that emissions per kg were neutral in this comparison, however. Additionally, energy return on total water input (including rainfall) in comparisons with conventional agroforestry and conventional monoculture were negative (Armengot et al. 2021). This trend was reversed when only considering the water footprint of the inputs. Many studies demonstrated enhanced carbon storage across different pools (i.e. in soil or aboveground) in organic agroforestry. For example, Häger (2012) assessed organic and conventional coffee agroforests and showed that organic agroforests stored more than 40% higher total carbon per hectare even if differences between individual carbon pools were not significant. Generally organic agroforestry is less energy intensive, stores more carbon and has lower emissions and climate impact than the other systems included in our comparisons.

Pollution, water and abiotic impacts

The majority of comparisons were positive with only total water footprint being negative in comparisons with organic and conventional monocultures (Fig. 1; Armengot et al. 2021). However, the transpiration rate of cocoa trees was lower in organic agroforests than in organic monocultures (Saavedra et al. 2020). Generally pollution levels, nutrient leaching and impacts on water systems are attenuated by organic agroforestry, especially in comparison to both monoculture systems, as reflected in the high weight of evidence scores for these comparisons(Fig. 2). Tully and Lawrence (2011) show that Nitrogen excess can be up to an additional 30 kg per hectare per year in conventional agroforestry versus organic agroforestry while excess Phosphorus can be more than four times higher in conventional agroforestry.

Pests, disease and weeds

Anthracnose disease incidence (*Colletotrichum spp.*) in coffee was higher in organic agroforestry compared to conventional agroforestry and organic monocultures (Piato et al. 2021), and both conventional systems had lower weed cover (Boinot et al. 2023). Aside from this, all other incidences of pests and diseases were mostly neutral (Fig. 1). Organic agroforestry supported higher predator density with more complementarity between predators than any other system (Boinot et al. 2020). Thus, the weight of evidence was neutral (~5) for comparisons to conventional agroforestry but slightly more positive for comparisons to the monocultural systems (Fig. 2).

Soil physicochemical properties, nutrients and fluxes

Generally this category yielded the most mixed results with many variables conflicting across studies (Fig. 1). Nonetheless, positive and neutral comparisons were still the most common resulting in relatively high weight of evidence scores (Fig. 2). The mineralization of 13 nutrients was overwhelmingly positive compared with conventional agroforestry, with only phosphorus mineralization being neutral. Several studies addressed nitrogen mineralization across every system- being neutral in comparison with conventional agroforestry, but mixed positive and neutral in comparison to the monocultural systems. The most conflicting results were in soil nitrogen and phosphorus concentrations yielding positive, neutral and negative comparisons depending on the study or system within a given study. Notably, Sauvadet et al. (2019), assessed two different agroforestry systems with different shade trees, one nitrogen fixing and the other non-fixing, and found that the positive effect on the soil was highly dependent on having a nitrogen fixing shade tree. This was also reflected in a plant bioassay they conducted in which plants cultivated in soil from sites with nitrogen fixing shade trees grew up to twice as much as those from other sites. Additionally, eight studies addressed soil carbon (see greenhouse gasses and energy) and found that organic agroforestry was mostly split between positive and neutral impacts.

Discussion

This review provides a checkpoint for research in organic agroforestry systems by systematically highlighting paired studies on organic agroforestry and alternative production systems. Across multiple variables, covering a large range of categories, organic agroforestry consistently compared positively against alternative systems (37% of all comparisons), with neutral outcomes being exceedingly common as well (42%). Negative comparisons were most prominent in relation to yields but were present to a minor extent in all categories (for a total of 9%). The remaining 12% of comparisons yielded mixed results (Fig. 1). The weight of evidence is also skewed positively across all categories and comparisons (Fig. 2), but is particularly high for Pollution, Water and Abiotic impacts as well as Socioeconomic factors. Given the broad range of positive comparisons and the relatively limited set of negative ones, organic agroforestry could represent a multifunctional system with few trade-offs. Importantly however, multifunctionality and specific trade-offs still need specific elucidation across a wider range of organic agroforestry systems.

Geographic distribution and studied crops

The bias of structured comparative research studies towards South America and their major agroforestry crops cocoa and coffee does not adequately reflect the global extent of agroforestry (see Zomer et al. 2009 for estimate) and further research into organic agroforestry should seek to alleviate this geographic bias. As cocoa and coffee have a long history of being grown, studied and marketed as agroforestry crops, this focus in literature is reasonable. While other crops are also native to the understorey of forest systems, these two crops could have a lighthouse function for agroforestry systems. The comparative nature of studies included here might also be a reason for the lack of studies on large-scale (agro-)silvo-pastoral systems in Europe (mediterranean, temperate and subarctic), Central Asia and Africa. Given organic agriculture's reliance on animal manure as fertilizer, it is surprising to see how few comparative studies address organic silvopastoral systems, although many may be organic-by-default and without certification. Considering the potential for enhanced carbon sequestration (Aryal et al. 2022) and the array of other benefits in such systems further research is warranted. The absence of studies on nut production, a food promoted by research as both healthy and sustainable (Willett et al. 2019), is also a research gap that should be addressed. Fruit trees were also underrepresented.

Quite a substantial amount of literature covers the impacts of agroforestry systems on arable crop production on the African continent. Yet the more development and extension focused character of these studies could be the factor preventing inclusion in this review (but see section on dryland agroforestry in the following paragraph).

Given the challenges of supplying adequate food security and nutrition, more attention should be paid to staple crops within agroforestry rather than cash crops, especially if organic agriculture wants to prove it can feed the world rather than solely provide high end goods.

Dryland agroforestry also received limited attention in comparison to agroforestry systems in wetter areas (Wu et al. 2021). Yet, dryland agroforestry holds a great potential in promoting sustainable land management and improving livelihoods in water-limited regions (Garrity et al. 2010; Sileshi et al. 2018). Many farms in dryland regions, particularly those in resource poor areas use little or no input, and hence can be considered by-default organic. Dryland ecosystems generally exhibit lower pest and disease pressure compared to temperate and tropical regions. The reduced humidity in drylands can limit the proliferation of certain pests and pathogens that thrive in moist environments. Similarly, nitrogen fertilizer application significantly influences crop productivity, but its efficacy can be compromised under water-stressed environments (Delgado-Baquerizo et al. 2013). Water deficit conditions can induce physiological changes in crops, such as reduced stomatal conductance and altered root architecture, further limiting the plants' ability to utilize applied nitrogen (Ye et al. 2022).

We were not able to identify a single comparative study conducted in drylands that would qualify as organic agroforestry by our criteria. However there are some studies in West African dryland agroforestry systems that provide a glimpse into potential performance of dryland organic agroforestry systems. For instance, in a long term (11 years) study, Bright et al. (2017) found no difference in soil C, N and P in agroforestry plots receiving no fertilizer versus various doses of synthetic fertilizer. They speculated that the presence of shrubs and their mulch, regardless of the fertilizers, improved soil quality. When the rainfall is adequate, however, fertilizer effect can be significant compared to no fertilizer in agroforestry systems (Dilla et al. 2019). Nevertheless, considering the current and predicted erratic rainfall in drylands, it is sensible to invest in approaches that are resilient in the face of climatic extremes, particularly in regards to N and C cycles (Delgado-Baquerizo et al. 2013). For example, some of the shrubs in West African dryland agroforestry systems are known not to compete with crops for water and, in fact, help crops to withstand the droughts by bringing water from deeper soil layers for utilization by crops (Kizito et al. 2012; Bright et al. 2021).

Biodiversity

A reasonable expectation is for biodiversity to be clearly higher in organic agroforestry in comparison to other systems due to enhanced habitat provision synergizing with the lack of pesticide use. The same expectation was held for belowground diversity due to: more abundant and diverse organic matter inputs with frequent input of leaf litter, more root exudates from a larger and more varied root architecture, more organic matter accumulation and less inhibition from pesticides and herbicides (Beaumelle et al. 2023; Ganault et al. 2021). However, in both cases while negative comparisons were sparse, most outcomes were neutral (Fig. 2). This perhaps suggests that while crop diversification and the absence of pesticides do increase biodiversity, they may not be additive to one another for the present taxa. This may also be a consequence of the responsiveness of the taxa included to management. For example, Durot et al. (2023) found that, while ant richness and array of trophic roles did not differ between all systems, each system had a unique assemblage. This study and references within demonstrate that ant richness is robust to management type, which may be the case for other taxa studied thus far.

Overall, the limited selection of taxa prevents general conclusions from being drawn as many more insect groups, and birds and mammals are yet to be studied in any organic agroforest. Yet given the biodiversity benefits of agroforestry generally (Beillouin et al. 2021), we expect further studies in organic agroforestry will likely indicate further benefits to a number of taxa at local and landscape scales, though it remains to be seen if organic agroforestry has additive or synergistic effects compared to organic agriculture and agroforestry generally.

Lori et al. (2022) showed that each system tends to have a unique assemblage of microorganisms, suggesting that microbial communities are capable of shifting to effectively utilize given inputs. Also, while less mycorrhizal colonization in organic agroforestry could be surprising, artificial fertilizers may stimulate mycorrhizal growth as suggested by Diaz-Ariza et al. (2021) and references within. A more suitable mix of shade trees may also have had an impact and further studies should investigate how to enhance mycorrhizal communities within agroforestry.

Three studies also highlight the need to control for native vs non-native species in biodiversity assessments in order to prevent false conclusions based solely on species richness (Marconi and Armengot 2020; Caudill et al. 2017; Cotter et al. 2017; Durot et al. 2023). Indeed, in planned agroecosystems, often incorporating non-native species, it is especially prudent to assess an agroforest's suitability for native species of all taxa and to use native analogues for, for example nitrogen fixing shade trees, wherever possible.

Importantly, studies that compare functional diversity across systems are lacking. Biodiversity when just measured as richness is a poor indicator of a well-functioning agroecosystem. Ecosystem functions and services can be optimized via the appropriate selection and cultivation of functionally distinct species (Willmott et al. 2023; Santos et al. 2021). Additionally, promoting the functional diversity of pest predators can provide a broader scope of pest control (Greenop et al. 2018).

Socioeconomic factors

Organic agroforestry generally promotes socioeconomic wellbeing in comparison to other systems according to the studies reviewed here, but less so in comparison to conventional agroforestry (Figure). Conventional and organic agroforestry were both more labor-intensive compared to monoculture systems but generally have outputs equivalent to or higher than conventional monocultures in terms of profit and calories produced (S1).

Given that input costs are lower, return on labor is higher and profit can be higher or equivalent, labor availability seems critical for organic agroforestry and agroforestry in general. Rosati et al. (2021) mention that this could be beneficial as increased labor requirements could create more jobs. This seems like an ideal case, however, and due consideration should be given to the fact that increased labor requirements may lead to agroforests being poorly managed due to time constraints, and/or unfair employment conditions and overwork. Organic premiums and certification requirements could attenuate this by ensuring farmers earn enough to pay for the extra labor required and by upholding standards that prevent exploitation. Taking this view promotes organic agroforestry over conventional agroforestry since it can facilitate a just attenuation of increased labor requirements where conventional systems would be unable to do so without other certifications.

Profitability can be enhanced, but not in every comparison or context. Profit seems most clearly enhanced in comparisons with organic monocultures (three studies), and, at least in Bolivian cocoa, costs are reduced in all comparisons due to at least a halving of fertilizer costs and minimal weeding costs (Armengot et al. 2016). No studies addressed the potential to gain additional income from enhanced ecosystem service provision, however, though this could be attributed to a lack of subsidies and other payment schemes in the study regions.

Jacobi et al. (2015) addressed aspects relating to resilience and knowledge acquisition. They found that "income sources" and crop diversification were neutral in comparison with conventional agroforestry, suggesting similar levels of resilience. Subsistence level was also comparable between agroforestry systems. However, organic agroforestry cultivation was positively related to information acquisition and affiliations to organizations suggesting that organic farmers may be better able to cope with the knowledge demands of organic agroforestry cultivation, providing them a higher adaptive capacity to respond to change. Unfortunately, we found no study quantifying farmers' perceptions of the increased knowledge demand and implementation difficulty of organic agroforestry.

Aside from the gaps previously mentioned, improved land tenure and stewardship remains to be studied as well as the market demand and access for organic agroforestry products. Additionally, studies addressing farmers' capacity to adapt to climate change were absent, and clearly more studies across a range of crops and sites need to confirm the potential economic benefits of organic agroforestry.

Yield

Our results indicate that switching from conventional agroforestry to organic agroforestry could have a positive or neutral impact on yields, potentially enabling farmers to gain higher income from organic premiums without a large reduction in yield. However, the few positive comparisons to conventional agroforestry may be due to study specific factors such as the use of vermicompost in Kumar et al. (2021) and no exogenous input management in both systems in Jacobi et al., (2015). For organic monocultures the impact of concurrent crop diversification on primary crop yields is conflicting and the few studies comparing organic agroforestry with conventional monocultures reveal lower yields for all primary crops with only total system yields being higher.

However, it is important to note that primary crop yield reductions may be the result of agronomic design rather than competition or shading because the incorporation of trees necessarily reduces production area. Only the studies on cocoa in Bolivia included in this review completely account for this by having an exact number of cocoa trees consistent across treatments (Pérez-Neira et al. 2023). Panozzo et al. (2020a) also measured olive yield per tree, but otherwise this effect remains unquantified in the literature on organic agroforestry, at least explicitly. This highlights the importance of quantifying and comparing system yields and LER in addition to individual crops yields.

Indeed, a focus on total system yields rather than on individual crop yields could enhance the appeal of organic agroforestry and agroforestry in general, especially considering the theoretically higher revenues that can be obtained (S1) and the higher calorie output (Pérez-Neira et al. 2023). However, this comes with non-trivial but surmountable technical and market issues (see Willmott et al., (2023)).

Both shade from agroforestry and the stress imposed on plants by organic agriculture have been shown to increase product quality in select crops (Çakmakçı and Çakmakçı 2023; He et al. 2021; Torrez et al. 2023; Elango et al. 2023), and given the high end market for organic agriculture, the potential for synergistic increases in quality should be investigated. Panozzo et al. (2020b) demonstrated this for wheat, but this was only attributed to shade as they didn't investigate conventional systems.

Overall, the limited evidence available suggests that organic agroforestry can enhance system yields and LER but only in comparison to organic monocultures (four studies across a diverse array of crops). Fewer comparisons have been made to conventional agroforestry and conventional monocultures but initial evidence from this review points to equivalent results to conventional agroforestry and positive comparisons to conventional monocultures. Thus, implementing agroforestry in organic systems may be a way to alleviate the yield gaps present in organic systems (Rosati et al. 2021).

Greenhouse gasses and energy use

Several studies mostly suggest that carbon storage is increased while emissions are reduced in organic agroforestry compared to the alternatives. Also, energy use is generally more efficient per unit production and there tends to be less reliance on non-renewable energy sources. Pérez-Neira et al. (2020) demonstrated that emissions per hectare and per kilogram of crop are lower in organic cocoa agroforestry compared to conventional monocultures, contrasting to the broader meta-analyses of Clark and Tilman (2017) and LG Smith et al. (2019). In spite of this, two studies (Noponen et al. 2012 and Reyes-Palomo et al. 2022) measuring differences in carbon footprint reported neutral outcomes in comparisons between organic agroforestry and all other comparison systems. In the first case, N_20 emissions from organic fertilizer and the decomposition of prunings from nitrogen fixing shade trees was a major contributor to the carbon footprint of organic agroforestry coffee, but high variability between farms suggests room for management optimization (Noponen et al. 2012). In the second case, in a Spanish silvopastoral system (Dehesa) deconstructing the carbon footprint only revealed significant differences in feed inputs, which were higher in conventional systems (Reyes-Palomo et al. 2022). Soil carbon sequestration was high but equivalent between silvopastoral systems. Also, while there were no reports of organic agroforestry having negative impacts on below- and aboveground carbon storage, there were frequent cases where it did not differ. Thus, further studies should address which management specifications can enhance carbon sequestration.

Pollution, water and abiotic impacts

Organic agroforestry may have less inputs that are a source of pollution compared to conventional systems and is also able to alleviate the leaching of inputs via a deeper and more widespread root system (Allen et al. 2004). These factors combined likely explain why most variables related to pollution were improved in organic agroforestry systems (Fig. 2). Nutrient leaching was also reduced in conventional agroforestry compared to conventional monocultures with no significant differences compared to organic agroforestry (Tully et al. 2013a, b). Thus, differences between these systems, such as eutrophication and ecotoxicity, could be due to the type and toxicity of the inputs unique to conventional systems (Armengot et al. 2021). These results are generally inconsistent with previous evidence that suggests organic inputs result in more eutrophication and acidification than conventional ones (Clark and Tilman 2017) meaning agroforestry may be a feasible solution to mitigate eutrophication and acidification resulting from organic inputs.

Aside from pollution related variables, water has received relatively little research in organic agroforestry, and further work should assess whether water use in these systems is more efficient due to potential synergistic effects of agroforestry and organic practices. Saavedra et al. (2020) did demonstrate that transpiration in cocoa trees is reduced in organic agroforestry compared to organic monocultures. Further to this, one could reasonably expect, for example, increased soil water holding capacity due to enhanced soil organic matter paired with more favorable microclimatic conditions leading to additional water use efficiency (Mensah et al. 2023).

Pests, disease and weeds

Organic systems tended to have higher weed cover and there was no evidence that organic agroforestry reduced this via pre-emptive occupation of niche space and shading (Santos et al. 2021).

Most pests and diseases seem to vary little between production systems in our analysis, but there is some evidence that agroforestry practices reduce the incidence of witches broom and stem borer in cocoa (Armengot et al. 2020), and whitefly in mixed vegetables cultivated under fruit trees and coffee. Contrastingly, anthracnose disease had a higher incidence in organic agroforestry (Piato et al. 2021). This could be due to the complex interactions anthracnose infection has with shade (Motisi et al. 2019). Based on previous research we would expect that entomopathogens of insect pests would be more prevalent in agroforestry systems due to stable microclimatic conditions and increased leaf litter and organic matter input into the soil (Moreira et al. 2019). However, Piato et al. (2021) showed that conventional coffee systems had almost double the incidence of the entomopathogen *Beauveria bassiana*, but suggest that this was due to higher pest infestation rates in conventional systems.

One study showed higher predator density and complementarity (Boinot et al. 2020) but it is unsure if this would translate into reduced pest prevalence.

Generally further research needs to assess if the potential biodiversity benefits of organic agroforestry translates into greater number of pest control agents and, importantly, a subsequent reduction in pest numbers. It is important to note however, that this is more likely to be the case when integrating specific pest control methods, such as barrier crops, push/pull plants, etc. (Jaworski et al. 2023), as well as integrating landscape level pest management (Mosomtai et al. 2021; Jaworski et al. 2023). Nonetheless, the evidence thus far doesn't suggest that pest-incidence is higher in organic agroforestry despite the absence of inorganic pesticides.

Soil physicochemical properties, nutrients and fluxes

The varied and often conflicting nature of the results found in this category reflects the complexity of managing an organic agroforestry system. Organic agriculture partially relies on input substitution and one of the main hypothesized benefits of organic agroforestry is that many of the inputs can be replaced by endogenous inputs from tree litter and prunings as well as crop residues. Indeed, Schneidewind et al. (2019) showed that the yearly nitrogen input from prunings of cocoa and its shade trees can substantially exceed the inputs of external fertilizers. Also, Asigbaase et al. (2021b) showed that organic management of cocoa agroforestry ensures nutrient return comparable to a system receiving synthetic fertilizers. Soil carbon was just as often higher as it was equal in organic agroforestry in comparison to the other systems, again suggesting management differences. The complexity lies in species selection that will eventually yield specific nutrients and soil properties; and this will depend on the starting state and type of the soil. This is illustrated by Sauvadet et al. (2019) who demonstrated that the outcomes of conventional versus organic coffee agroforestry cultivation differ greatly depending on whether a nitrogen fixing shade tree is cultivated or not. Using a plant bioassay, an indicator of overall soil fertility, they showed that soil from organic agroforestry under a nitrogen fixing shade tree induced the highest plant growth while organic agroforestry under another shade tree induced the lowest. Importantly however, the sites had sufficient phosphorus, and nitrogen was likely to be the most limiting factor. Overall, given the available evidence, we cannot support the hypothesis that organic agroforestry improves soil quality. Rather it can improve soil quality under the correct conditions and with the correct management.

Conclusion

Based on the studies analyzed for this work, organic agroforestry improves a considerable array of biophysical and socio-ecological factors (such as pollution, nutrient leaching and nutrient mineralization) when directly comparing it to alternative systems. For some factors (such as most pests, diseases and soil microbes), comparisons result in insignificant differences. Drawbacks tended to be uncommon in studies addressing this topic so far, and those that were found may be overcome by altering the management of organic agroforests and market conditions for organic agroforest products. Nonetheless, the significant bias towards research in South America on coffee and cocoa hinders the generalizability of our results. Given that comparisons in single crop yields accounted for a large proportion of the negative results, further work should address how to overcome this, and also whether this pattern may be a consequence of addressing single crops rather than whole system yields and land equivalent ratios. More work is also needed to address staple crops and those promoted as sustainable and healthy, such as nuts, rather than the current focus on cash crops in the literature. This should be paired with the expansion of the geographic range of studies, particularly to regions that may especially benefit from organic agroforestry such as dry lands. Additional economic and market research is needed to address if the organic agroforestry production is in line with the organic price premiums, demand, market access, potential payments for ecosystem services, and ethical labor practices.

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