

Organic management in coffee: a systematic review of the environmental, economic and social benefits and trade-offs for farmers

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ABSTRACT

Global coffee production is expanding, contributing to environmental degradation, notably through extensive use of inorganic fertilizers. Volatile prices, climate change, rising input costs, and pressure to decrease carbon footprints represent key challenges for farmers. Regenerative soil management and the use of organic management as an alternative to conventional mineral fertilizers offer one potential solution to address these challenges. However, information is limited regarding the potential options available for farmers, and their potential environmental, economic, and social impacts. We undertook a systematic review of the literature to assess the benefits and trade-offs from adopting different organic management approaches following PRISMA guidelines. We identified 43 peer-reviewed articles, predominantly focusing on agroforestry, plant-derived additions, soil management or animal manure to improve livelihoods and environment. Research priorities differ by region and there is a skew toward researching the environmental impacts of regenerative techniques. Our synthesis demonstrates multiple potential environmental benefits to organic management, but increasing economic risks and trade-offs for farmers, particularly in transitioning to organic management. We also highlight the social barriers facing farmers, from education to access to knowledge networks to support implementation. These challenges must be addressed to support any future sustainable transitions to organic management in coffee.

KEYWORDS

Agroforestry; intercropping; Sustainability; Arabica; Robusta

Introduction

Coffee is one of the most highly consumed beverages globally with over 160 million 60 kg bags consumed between 2020 and 2021 (Ridder 2022). Coffee production supports the livelihoods of 25 million smallholder farmers (Waller, Bigger, and Hillocks 2007) that grow up to 80% of global supply

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(Acosta-Alba et al. 2020; Anderzén et al. 2021). The global coffee industry is valued at over \$200 bn (ICO 2020) and predicted to continue growing at over 4% per year (Mordor Intelligence 2022), with growth driven in particular by increased consumer demand for certified and specialty coffee as consumer interest grows in the source, sustainability, and carbon footprint of coffee (Chemura 2014; ICO 2020; Wulandari, Ferry, and Hasibuan 2022).

While coffee production has risen by 60% over the last 30 years (ICO 2020), oversupply has contributed to volatile prices (Anderzén et al. 2021; Chemura 2014; Guido, Knudson, and Rhiney 2020; Jezeer et al. 2019). Many coffee farmers, particularly smallholders, are unable to achieve a living income from coffee (ICO 2020; Wairegi et al. 2018). Even before the COVID-19 pandemic destabilized global supply chains, including those of the coffee industry (Guido, Knudson, and Rhiney 2020; Stanbury 2020), the International Coffee Organisation (ICO) was already referring to the reduction of coffee prices by 30% as a “price crisis” (ICO 2019a). This can have environmental impacts; for instance, 62% of farmers reduced their investments in coffee production between 2016 and 2018 even as fertilizer prices increased in the same period (ICO 2019b), reducing investment in inputs to maintain productivity, for example by reducing fertilizer applications, and pest management (Hagggar et al. 2017; ICO 2019b).

Fertilizers are essential for maintaining coffee yields (Chavez et al. 2021; Fernando et al. 2019). Coffee needs nitrogen and other nutrients to produce coffee berries – harvesting a ton of coffee removes 33–63 kg of nitrogen from the farm ecosystem, 2–11 kg P_2O_5 , and 47–67 kg K_2O (Byrareddy et al. 2019; Descroix and Snoeck 2008). However, conventional production is widely considered to be detrimental in the longer term – not only are inorganic fertilizers out of financial scope for many smallholders due to a lack of capital and low coffee prices (Kudama, Wana, and Dangia 2021), they also contribute toward environmental degradation (Rahmah et al. 2022), for example through the production and emission of greenhouse gases (GHGs), including nitrous oxide (N_2O) a highly potent and long-lasting GHG (Rebello et al. 2022), and nitrogen run-off and leaching (Cannavo et al. 2013; Tully, Lawrence, and Scanlon 2012). Extensive literature highlights the current inefficiencies of production systems, and opportunities for enhanced efficient nutrient management within farms (Freitas et al. 2022; de Souza et al. 2023). Thus, there is impetus at a national and international level to reduce and/or optimize inputs where possible.

While improved nutrient management through organic approaches can enhance nutrient retention and provide fertility and environmental benefits, these do not necessarily result in direct financial benefits for farmers unless the cost of such approaches is lower than the conventional management it replaces. Transitioning to organic inputs also does not mean that farmers are immediately meeting the requirements for organic certification (Jones et al. 2024), which can require wider systems change, for example through

changes in pest management that reduce broader agrochemical inputs. However, organic certification, for which demand is growing, can, although not always, lead to better pricing benefiting farmers (Wulandari, Ferry, and Hasibuan 2022). Another impetus to reduce inorganic fertilizer use is the substantial price increases in fertilizers since 2020 (Perez 2022), adversely impacting the livelihoods of the estimated 125 million people who depend on the coffee supply chain for income (Voora et al. 2019).

Alongside environmental pressures, and volatility in prices, farmers are also facing increasing volatility in climate, with higher temperatures and unreliable precipitation impacting coffee (Bezner Kerr et al. 2022). Robusta coffee, grown largely in South and East Asia, is more tolerant of hotter and drier conditions (Coffee Research Institute 2022) than the Arabica species, which currently represents about 70% of global production (Scott 2015) and dominates in Africa and Latin America. Arabica coffee grows best in temperatures averaging 18–21°C (Coffee Research Institute 2022), and as temperatures increase, bean quality reduces (Scott 2015).

Climate change is further reducing the resilience of coffee production, representing a threat to farmers' livelihoods and to future supply. Global coffee-growing land is projected to decrease by 50% by 2050 (Grü et al. 2022), potentially reducing Arabica production by 45.2% and Robusta production by 23.5% by 2099 (Adams et al. 2021). In response, coffee farmers need to take action to protect their livelihoods, including investigating opportunities for improved nutrient management to reduce costs, optimize nutrient regimes, and address broader sustainability challenges. Organic management practices in coffee can reduce the carbon footprint of coffee production through reduced GHG emissions including highly potential N₂O emissions, which makes transitioning of potential value for climate change mitigation, and through potential economic opportunities associated with certification, assuming other requirements are met (Rahn et al. 2014; Jones et al. 2024). Agroforestry systems can provide an additional nitrogen source (if nitrogen-fixing species are planted), reducing external inputs, with shade trees also reducing temperatures amongst other benefits, maintaining crop production under a changing climate (Bracken, Burgess, and Girkin 2023). However, adoption of these and other practices requires an enabling environment at national and global levels, to continue to meet growing global demand and protect a substantial global industry (Haggard and Schepp 2012).

Low and volatile prices, climate change, rising input costs, pressure to decrease the carbon footprint and environmental degradation during production, and the rising demand for sustainably produced coffee represent a raft of challenges for coffee farmers. There is thus a pressing need to improve the sustainability of coffee production – addressing the three pillars of sustainability, notably the environmental, economic and social challenges (Behrens, Bosker, and Ehrhardt 2020) and in line with the UN Sustainable Development

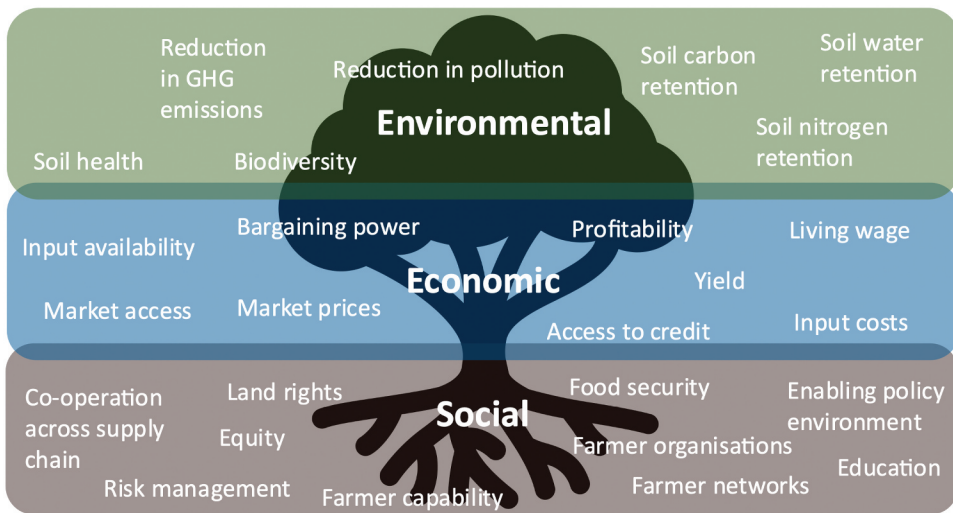


Figure 1. Integration of elements of environmental, economic and social sustainability relating to coffee production.

Goals. This is a holistic approach that requires consideration of the interconnections inherent in the goal of creating sustainable food systems that provide nutrition for a growing population and decent livelihoods for those who produce our food, while operating within environmental boundaries to protect biodiversity, mitigate against climate change, maintain soil and water resources and reduce environmental damage from pollutants (le Blanc 2015; Rockström et al. 2017) (Figure 1).

There are a variety of farm management practices increasingly adopted by the sector, from larger agribusinesses to smallholder farmers, which are recognized as providing various potential environmental benefits, including intercropping, agroforestry, and organic management (Bracken, Burgess, and Girkin 2023). Such practices are sometimes used in isolation, or frequently in combination, and are often referred to individually or collectively as examples of “regenerative” (Bracken, Burgess, and Girkin 2023), or “agroecological” farming (Leakey 2014; Morris et al. 2016; Perfecto and Vandermeer 2015). These practices are considered to provide broad benefits to soil health, climate resilience, and ecosystem productivity (Grossman et al. 2020). In the context of coffee production, increased retention of nutrients, particularly, nitrogen, phosphorus, and potassium within soils enhances sustainability and productivity (Byrareddy et al. 2019; Tully, Lawrence, and Scanlon 2012), while the associated changes to soil health from changes in organic matter content also aid water retention while mitigating against nitrogen leaching (Le et al. 2021). Such practices do not necessarily require the elimination of artificial fertilizers, but by focusing on soil health and making use of biological nutrient management through available materials such as manure and plant waste on-farm, require low to no external inputs (Grossman et al. 2020).

Within smallholder coffee farming systems in particular, there can be a high degree of variability in practice, including in terms of nutrient management, with varying resultant impacts on soil health, productivity, and ecosystem dynamics (Castro-Tanzi et al. 2012).

Previous systematic reviews of these challenges (e.g. Bracken, Burgess, and Girkin 2023) have either focused broadly on holistic regenerative or agroecological farming practices in coffee, and opportunities for new and emergent trends in fertilizer technologies (e.g. de Souza et al. 2023), but have not specifically explored opportunities for organic management. Such trends have been investigated in other crops (e.g. tea in Rebello et al. 2021), but their applicability to the coffee sector is limited given different management requirements. In this study, our central aim is to assess the benefits and trade-offs from the increasing adoption of organic management practices for coffee production. Here, we conducted a systematic review of the global literature to assess impacts of such changes for farmers, the environment, and for the future of the global coffee supply, using the three pillars of sustainability to provide a framework through which to understand whole system changes from such transitions, i.e. in terms of social, financial, and environmental benefits and trade-offs.

Methodology

A systematic literature review was conducted following the methodology proposed by Pickering and Byrne (2013) (Figure 2). First, a well-defined research question was identified, using the PICO and SPIDER frameworks as outlined by (Cooke, Smith, and Booth 2012) as reference tools: *what are the social, financial, and environmental benefits and trade-offs for farmers in adopting organic nutrient management practices?*

Articles were identified via abstract, title, and keyword searches via two databases: SCOPUS and Web of Science, using the following keywords (*coffee AND fertiliser*) AND (*livelihood OR nitrogen OR productivity OR yield OR organic OR income OR econom**), generating 668 articles on 23rd May 2022 from SCOPUS, and 302 articles from Web of Science. A total of 253 duplicate articles were subsequently removed, followed by errata and notes, leaving 714 articles. Articles were subsequently eliminated sequentially, beginning with studies outside the scope of the study, which included a large body of literature on the use of spent coffee grounds at a post-consumer stage, as were book chapters, conference proceedings, and technical reports, as they are not necessarily peer-reviewed. To be included, articles needed to focus on production, and at least one of the three pillars of sustainability: the environment, society, or economy. To assess research literature over the last 10 years, pre-2012 publications were removed, with 58 remaining. Abstracts were then read in detail, eliminating additional papers not

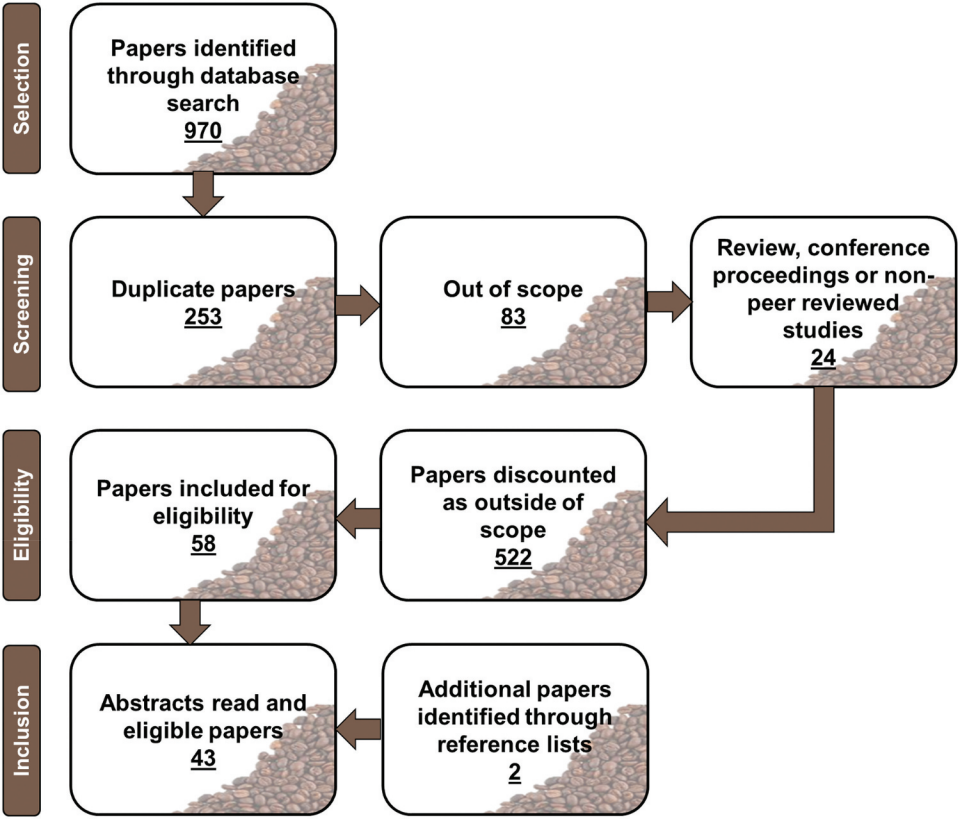


Figure 2. PRISMA approach to the systematic literature review.

Table 1. Categorization of articles in the systematic review.

Categorisation	Details
Location of the study	The country, countries or region at a sub-continental scale (UN 2022)
Scale of the study	From a glasshouse, to a farm, regional or country scale
Coffee type	Focus on Arabica, Robusta or kopyol beans
Sustainability focus of study	Environmental, economic or social, or a combination
Type of practice	The production method (s) to examine organic nitrogen management that the article focused on, which were then grouped together (see Table 2 for definitions)
Scale of farming	Smallholder or agribusiness

in scope. Two additional articles were identified during the review process and incorporated into the study. Articles were categorized according to their sustainability focus on environmental, economic, or social aspects of coffee production and a final shortlist of 43 articles were identified for inclusion in the review. The five articles in languages other than English were translated using Google Translate, and efforts were made to verify the accuracy of the translations. By restricting the scope primarily to indexed English Language studies, it is possible that additional publications containing local and Indigenous insights in key

Table 2. Organic management: definitions, descriptions, and author focus within the systematic review.

Practice	Definition and description	Intended consequence for farmer livelihoods and farm/wider ecosystem	Level of system change	Reference(s)
Animal manure	Use livestock manure to fertilise coffee	Contributes towards soil health, adds nutrients and reduces the need for inorganic fertilisers.	Low, through replacement of other fertiliser management practices	Basavalingaiah et al. (2022); Byrareddy et al. (2019); Fernandes et al. (2013); Fernando et al. (2019); Guteta and Abegaz (2016); Hasibuan, Ferry, and Wulandari (2022); Kurniawan, Hariyanto, and Ishaq (2021); Martins Neto et al. (2020); Mosquera et al. (2016); Rahmah et al. (2022); Torres-Jiménez et al. (2020); Vera-Acevedo, Vélez-Henao, and Marulanda-Grisales (2016); Wardani, Meidaliyantisya, and Rivaie (2021); Wulandari, Ferry, and Hasibuan (2022)
Liquid organic fertiliser	A liquid form either derived from plants through manufacturing, or directly from animals as urea	Liquid organic fertiliser contributes nutrients to the soil, and reduces the need for inorganic fertilisers.	Low, through replacement of other fertiliser management practices	Rahmah et al. (2022)

(Continued)

Table 2. (Continued).

Practice	Definition and description	Intended consequence for farmer livelihoods and farm/wider ecosystem	Level of system change	Reference(s)
Plant-derived additions	Plants grown to cover the soil, and can then be dug into the ground, or cut down or pruned and added to the soil. Includes pruned coffee branches	Adding green manure contributes towards soil health, contributes nutrients, and when leguminous plants are used, contributes additional nitrogen lost from coffee harvest.	Low, through replacement of other fertiliser management practices	Araujo et al. (2013); Basavalingiah et al. (2022); de Oliveira et al. (2015); Fernandes et al. (2014); Hasibuan, Ferry, and Wulandari (2022); Martins Neto et al. (2020); Silva Araujo et al. (2014); Wulandari, Ferry, and Hasibuan (2022)
Compost	Plant material or waste left to rot, fermented, or used to feed worms in vermiculture, and then added directly to the soil	Compost contributes towards soil health, contributes nutrients, and reduces the need for inorganic fertilisers.	Low, through replacement of other fertiliser management practices	Araujo et al. (2013); Byrareddy et al. (2019); Chemura (2014); Guteta and Abegaz (2016); Kariada and Arsana (2019); Martins Neto et al. (2020); Mosquera et al. (2016); Rahmah et al. (2022); Vera-Acevedo, Vélez-Henao, and Marulanda-Grisales (2016)
Mulch	Plant material or plant waste added to the top of the soil	Mulch contributes towards soil health, contributes nutrients and reduces the need for inorganic fertilisers.	Low, through replacement of other fertiliser management practices	Bucagu, Vanlauwe, and Giller (2013); Mosquera et al. (2016); Nzeyimana et al. (2020)
Plant waste	Dead leaves, fallen branches, waste and pulp from processing coffee or other plant waste added to the soil	Plant waste grown elsewhere or from intercropping or shade (see below) contributes towards soil health, contributes nutrients and reduces the need for inorganic fertilisers.	Low, through replacement of other fertiliser management practices	Byrareddy et al. (2019); Hasibuan, Ferry, and Wulandari (2022); Karim, Hifnalisa, and Manfarizah (2021); Martins Neto et al. (2020); Golinucci et al. (2022); Wulandari, Ferry, and Hasibuan (2022)
Biochar	Plant material carbonised under high temperatures to produce a carbon-rich substance	Biochar contributes towards soil health, particularly due to its ability to improve water retention and nutrient retention of soil, and reduces the need for inorganic fertilisers.	Low, through replacement of other fertiliser management practices	Melaku et al. (2020)

(Continued)

Table 2. (Continued).

Practice	Definition and description	Intended consequence for farmer livelihoods and farm/wider ecosystem	Level of system change	Reference(s)
Agroforestry Shade	Planting trees that provide shade to coffee. Often also referred to as agroforestry, with both trees and coffee plants as the woody perennial and/or crop	Trees improve soil health, particularly by helping to prevent soil erosion and soil loss. Leguminous trees can provide extra nitrogen, while dead leaves, cuttings, fallen branches and other plant waste can be used as plant-derived additions, enhancing nutrient and organic matter retention. Shade reduces coffee tree temperatures, thus reducing evapotranspiration. Shade trees can also provide income diversification and contribute to food security by selecting fruiting or timber species.	High, assuming current cropping density is insufficient to allow integration of shade trees	Babin (2015) Bote and Vos (2017); Chatterjee et al. (2020); Chavez et al. (2021); de Oliveira et al. (2015); Guteta and Abegaz (2016); Haggard et al., 2021; Jezeer et al. 2018; Karim, Hifnalisa, and Manfarizah (2021); Kuswadi and Fitriani (2021); Le et al. (2021); Pronti and Coccia (2020); Sarmiento-Soler et al. (2020); Golinucci et al. (2022); Tully, Lawrence, and Scanlon (2012)
inter-cropping	Planting a different crop, or a number of different crops, in-between coffee. In coffee, intercropping is also considered agroforestry, with coffee as the woody perennial	Intercropping can provide shade (see above) and plant waste for other plant-derived soil additions (see above), while growing multiple crops can provide a diversification of income and/or food security. Leguminous intercrops can provide extra nitrogen to the soil.	Low, assuming current cropping density allows for intercropping	Bucagu, Vanlauwe, and Giller (2013); de Oliveira et al. (2015); Golinucci et al. (2022); Mosquera et al. (2016); Pronti and Coccia (2020); Sarmiento-Soler et al. (2020); Thuy, Niem, and Lebailly (2020)
Livestock integration	Allow livestock to graze around coffee. This is considered agroforestry, with coffee as the woody perennial	Livestock manure contributes towards soil health, contributes nutrients and reduces the need inorganic fertilisers. Livestock can contribute to food security and/or diversification of income.	Medium, requiring breeds adapted to coffee growing areas, animal waste management, and additional potential infrastructure (e.g. fences)	(Kuswadi and Fitriani 2021)
Trenches for soil management	Digging trenches next to or around coffee trees	Trenches can improve soil water retention and reduce erosion by catching run-off, and can also be used as a repository for plant and animal derived additions	Medium, as requires extensive physical labour, and may result in crop loss in field margins	Wardani, Meidaliyantisyah, and Rivaie 2021

coffee producing nations may have been missed. The remaining articles were then categorized based on region, coffee variety, and practice (see [Table 1](#) for categorization, and [Table 2](#) for definitions of production methods for organic nutrient management).

While rigorous, the systematic approach can have limitations. First, the ability to select articles based on keywords, titles, and abstracts relies on those elements being constructed to clearly communicate the entire content of the article, and risks missing relevant articles during selection. Criteria used to eliminate articles as out of scope can be subjective; to help mitigate against this, this review captured studies in languages other than English, using translation to enable inclusion. Second, wider research highlighted a range of reports, articles, and policy papers, not available via SCOPUS or World of Science, that yielded high-quality data, information and insight on organic management in coffee, including the UN, World Coffee Organisation, FAO, Ethical Trading Initiative, and private research bodies. While these may be produced in a slightly different way, and may have an inherent bias, they can also bring a different and valuable perspective. Finally, the necessarily narrowed search through keyword selection goes contrary to the integrated nature of sustainability when viewed holistically (Behrens, Bosker, and Ehrhardt 2020, 5). For example, this study does not include the interactions of organic management practices with pests and diseases, genotype, and other nutrients for instance (Hillocks, Phiri, and Overfield 1999; Pérez et al. 2019; Resende et al. 2022). Some articles in the systematic review indicated that these have important interactions with productivity and therefore influence farmers' decision-making (Jezeer et al. 2018; Wang et al. 2015).

Not all articles could be fully categorized; 24% of articles did not specify variety of coffee, while 32% did not explicitly mention a focus on smallholder coffee production or agribusiness (61% focused on smallholders, and 7% focused on both smallholders and agribusiness). Moreover, where a focus on smallholders was specified, the scale of production varied widely from < 1 to >10 ha in coffee production. This is an important constraint in the context of the review. Not only can there be a huge difference between the potential capacities of farmers operating at widely differing scales to transition to organic management but there is also a limitation in what the review can do to make recommendations for smallholder farmers in any given context, given that their peers, while categorized in the same way, may be producing coffee in very different circumstances. No articles were identified that referred to the specific circumstances of out-growers, namely smallholders who may operate at a variety of smaller scales but whose

relationship with a buyer or processor may have implications for organic management.

Results and discussion

Research priorities differ by region

The geographical distribution of articles selected broadly reflected the distribution of global coffee production, apart from West and Middle Africa, for which no articles were identified. There were more articles focused on South America and South-East Asia than other regions (Figure 3). However, the distribution of articles did not reflect so clearly the distribution of countries most reliant on coffee exports; nine of the 10 most heavily dependent on coffee as an export commodity are in Central America and East Africa, where fewer studies were focused. This may in part be a function of the volatility of coffee prices themselves. During periods of lower prices – such as post-2016 when prices have been below the 10-year average (ICO 2020) – there was less funding for research in countries where research into coffee is heavily dependent on taxation from coffee exports for its funding (Hartman 2020).

The reviewed studies showed contrasting research priorities in different regions (Figure 4). For example, there appeared to be a trend toward focusing on economic sustainability in East Africa, a focus on economic/environmental sustainability in East Asia, and a greater focus on environmental sustainability in South America. To some extent the emphasis in East Africa may reflect the reliance on coffee as a commodity for the economy of several countries in this

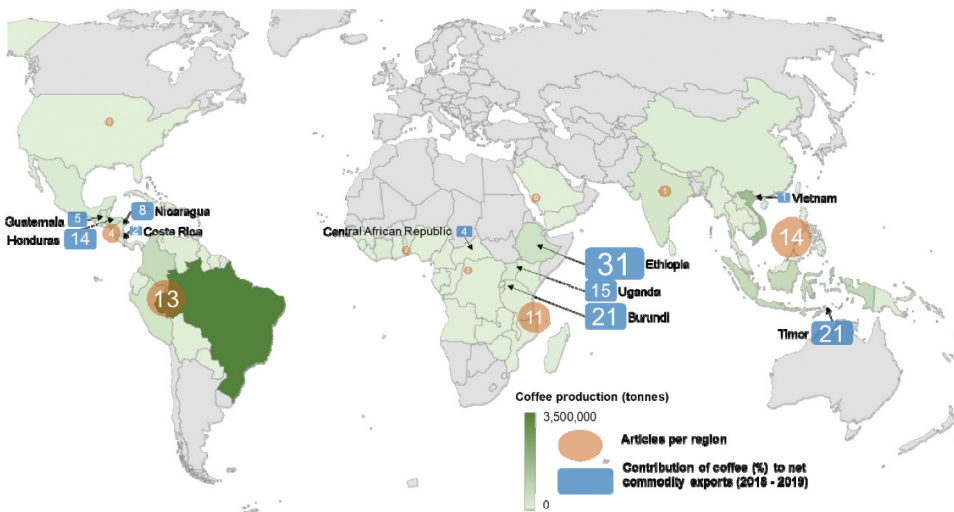


Figure 3. Distribution of studies in major coffee producing countries and regions.

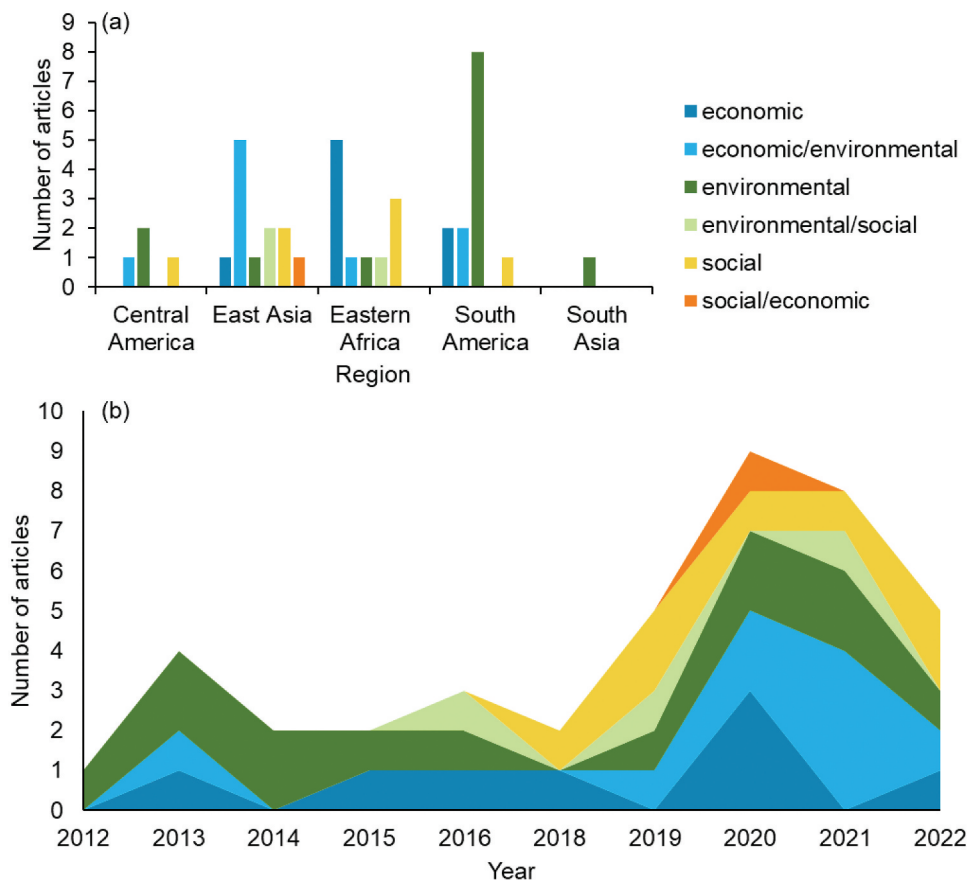


Figure 4. (a) Regional categorisation of studies; (b) changes in study categorisation over time.

region. A key driver in sustainability here is to ensure sustainable livelihoods that can withstand, or even overcome, some of the price volatility in coffee. In research focused on coffee in East Asia, it is more likely to be concerned with Robusta coffee, and so the research trends generally reflect concerns about the profitability of Robusta coffee which sells for a much lower price than Arabica (International Coffee Organisation 2022).

Several articles focused on East Asia saw certification as improving farmers' livelihoods through more stable and higher prices (Hasibuan, Ferry, and Wulandari 2022; Le et al. 2021; Rahmah et al. 2022; Wulandari, Ferry, and Hasibuan 2022). This may also account for the additional focus on the environmental angle as certification standards such as Fairtrade, Rainforest Alliance and organic all focus to a greater or lesser extent on the minimization of harmful chemicals and the promotion of agroecological agricultural techniques (Traldi 2021).

A growing focus on environmental sustainability

There has been a gradual increase in research on organic management in coffee over the last 4 years, with the number of articles per year increasing since 2019 compared to previous years (Figure 3b). There has also been a gradual shift away from articles that tend to focus on one pillar – either economic or environmental sustainability, looking at the effects of management practices on, for instance, farmers' yield or income, *or* the impact on soil, biodiversity, or environmental protection – to articles that focus on two areas (Figure 4). This is accompanied by a growing interest in social aspects of sustainability such as risk management in decision-making, co-operatives, farmer education, and the role of policy and enabling environments in fostering change. However, there remains an emphasis on environmental aspects.

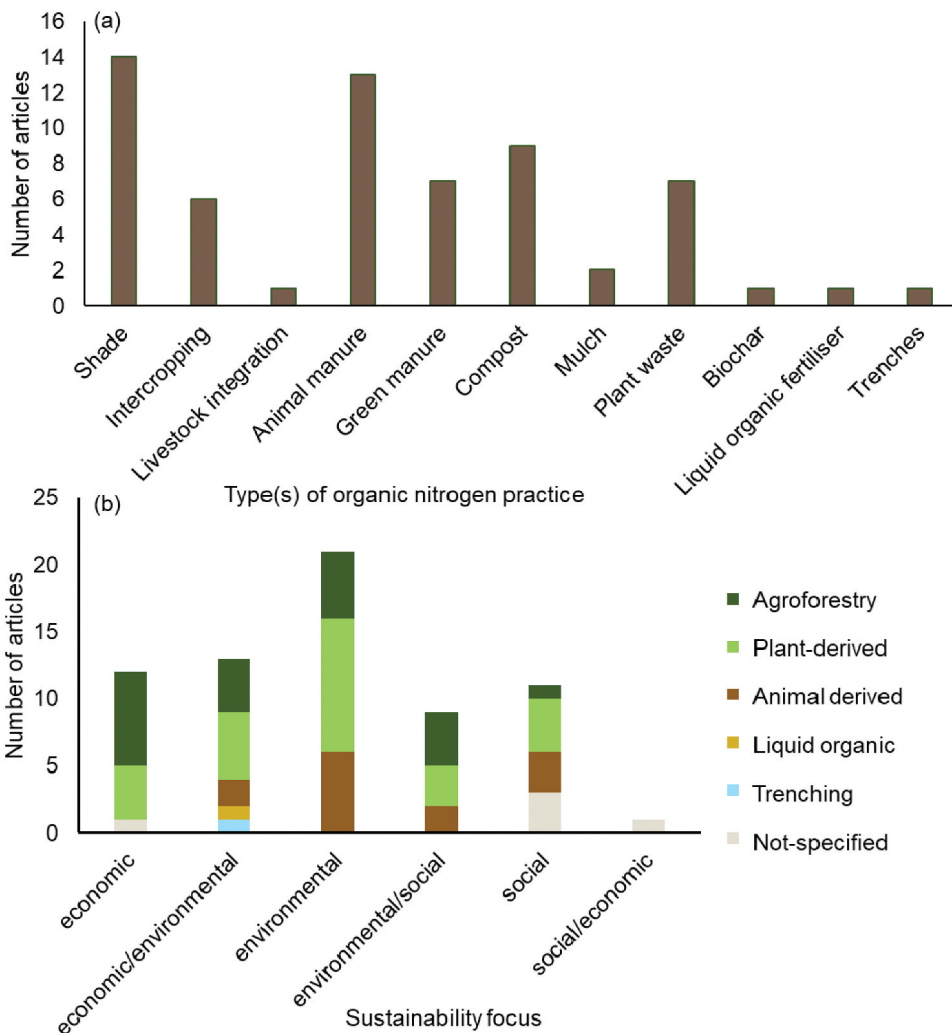


Figure 5. Categorisation of articles by sustainability focus – economic, social or environmental sustainability, or a combination.

Several articles focused on the impact on organic management of particular shade, intercropping or green manure species (Araujo et al. 2013; de Oliveira et al. 2015; Fernandes et al. 2014; Fernando et al. 2019; Karim, Hifnalisa, and Manfarizah 2021; Kurniawan, Hariyanto, and Ishaq 2021; Martins Neto et al. 2020; Silva Araujo et al. 2014) (Figure 5(a)). There were more articles focusing on shade and animal manure than others, while five articles did not specify a practice, or were not specific enough, to be categorized; all of these had a social and/or economic focus.

Many studies focus on specific treatment regimens to test whether a particular addition has a positive or negative impact on soil health, nutrients, and yield. On the other hand, the lack of focus on the economic impact of particular additions, or the social dimensions related to them, results in a lack of insight into their wider impact on livelihoods, and a lack of clarity for policy makers, co-operatives, farmer institutions and other relevant bodies to create the right enabling environment for change.

It is worth noting that despite dominating global coffee production, Brazil is less reliant on coffee in terms of exports than many other agricultural products (Workman 2022). Fewer than 10% of coffee farmers in Brazil rely on coffee for their livelihoods, compared to farmers in Honduras, Rwanda, Papua New Guinea and Uganda, where coffee is the main source of income for over three-quarters of farms where it is grown (ICO 2019b). This might to some extent explain the skew observed in articles focusing on environmental sustainability in South America. At a farm or national level coffee revenues generated from farms are perhaps less fundamental for income, but there is an interest at a global level in halting environmental degradation and deforestation in Brazil. The focus on Arabica production in South America might also account for this skew; it is more sensitive to climate change, with shade and organic additions to the soil seen as adaptation techniques as conditions get warmer and drier (Jezeer et al. 2018, 2019).

Research provides insight into a range of organic management techniques and identifies many benefits and risks

Overall, the articles identified indicate a wide range of risks and barriers, and opportunities and benefits, of organic management for coffee farmers. The risks – mostly economic – and barriers – mostly social – for farmers are outlined in Table 3.

The benefits and opportunities of organic management with a low input system, strongly tend toward the environmental, but research also pointed to some economic benefits, particularly where this also included a diversification of income. The review demonstrates a wide range of routes for organic management, particularly around plant-derived inputs, with differing effectiveness at replacing nutrients lost from the soil through

Table 3. Risks of, and barriers to, organic management for coffee farmers.

Risk or barrier associated with organic management	Impact	References
Economic risk: low and volatile prices for coffee	Prevents farmers from investing in their production	Jezeer et al. (2018); Golinucci et al. (2022); Wairegi et al. (2018); Wulandari, Ferry, and Hasibuan (2022)
Economic barrier: Poverty or lack of finance; lack of access to credit	Prevents farmers from investing in their production	Byrareddy et al. (2019); Jezeer et al. (2018); Kudama, Wana, and Dangia (2021)
Social barrier: Lack of field/agronomic education amongst farmers	Prevents farmers from optimising production, improving production methods or having the confidence to experiment with innovative techniques	Guteta and Abegaz (2016); Jezeer et al. (2019); Kudama, Wana, and Dangia (2021); Kuswadi and Fitriani (2021); Mulinde et al. (2019); Torres-Jiménez et al. (2020)
Social/economic barrier: Reliance on costly or scarce manual labour	Prevents farmers from optimising production, improving production methods by replacing inorganic management techniques with agroecological ones that have higher labour needs	Haggar et al., 2021; Jezeer et al. (2019); Kudama, Wana, and Dangia (2021); Thuy, Niem, and Lebailly (2020); Wulandari, Ferry, and Hasibuan (2022)
Social barrier: Lack of general education amongst farmers	Complex interaction between education levels and organic management	Golinucci et al. (2022); Kudama, Wana, and Dangia (2021); Torres-Jiménez et al. (2020); Yusmarni et al. (2020)
Economic risk: the likely or perceived yield penalty, particularly during the transition to organic management	Prevents farmers from having the confidence to experiment with innovative techniques	Basavalingaiah et al. (2022); Bucagu, Vanlauwe, and Giller (2013); Chemura (2014); Fernandes et al. (2013), (2014); Jezeer et al. (2019); Le et al. (2021); Nzeyimana et al. (2020); Silva Araujo et al. (2014)
Economic barrier: lack of adoption of technology for farm management	Puts limits on farmers' insights on what their coffee production needs, the effectiveness of production, and what farmers have the capacity to change in production	Martins Neto et al. (2020); Rahmah et al. (2022); Yusmarni et al. (2020)
Social/economic barrier: a lack of strong farmer institutions	Where these exist, they provide advice, training, support and bargaining power for farmers	Jezeer et al. (2019); Kudama, Wana, and Dangia (2021); Mulinde et al. (2019); Wulandari, Ferry, and Hasibuan (2022)
Structural barrier: the lack of a coherent policy environment	Policy to coherently support transition to organic management facilitates the removal of multiple other barriers	Mulinde et al. (2019); Torres-Jiménez et al. (2020)
Social barrier: Experience and age of farmers	Complex interaction with organic management	Mulinde et al. (2019); Wulandari, Ferry, and Hasibuan (2022); Yusmarni et al. (2020)

coffee production by species involved (Descroix and Snoeck 2008; Byrareddy et al. 2019), and in any given locality, as they interact with local soils and climate. While all have some effectiveness, particularly intercropping or soil additions from leguminous plants or crops (Bucagu, Vanlauwe, and Giller 2013; Chavez et al. 2021; Martins Neto et al. 2020), less research has been conducted with biochar, with only one study included in the review acknowledging that more research is needed to

Table 4. Benefits of organic management for coffee farmers, the coffee farm environment and wider environment.

Potential benefit of organic management	Impact	References
Economic/environmental: <i>Reducing (but not eliminating) the use of inorganic inputs</i>	Reduction of the costs of production; reduction in environmental pollution and GHG emissions	Babin (2015); Basavalingaiah et al. (2022); Bizimana, Nieuwoudt, and Ferrer (2002); Byrareddy et al. (2019); Chavez et al. (2021); Kariada and Arsana (2019); Kuswadi and Fitriani (2021); Le et al. (2021); Rahmah et al. (2022); Wulandari, Ferry, and Hasibuan (2022)
Environmental: <i>The use of organic techniques using</i> 1) animal manure 2) green manure 3) mulch and/or trenches 4) compost, or 5) intercropping or agroforestry	Improved soil health and/or nutrient availability in the soil	(1) Fernandes et al. (2013); Fernando et al. (2019); Kurniawan, Hariyanto, and Ishaq (2021); Mosquera et al. (2016); Thuy, Niem, and Lebailly (2020) (2) Araujo et al. (2013); Fernandes et al. (2014); Martins Neto et al. (2020); Silva Araujo et al. (2014) (3) Wang et al. (2015); Wardani, Meidaliyantisah, and Rivaie (2021) (4) Mosquera et al. (2016) (5) de Oliveira et al. (2015); Kuswadi and Fitriani (2021); Thuy, Niem, and Lebailly (2020); Bote and Vos (2017)
Economic/environmental: <i>Reusing farm or coffee waste to replace inorganic inputs</i>	Reduction of the costs of production; reduction in environmental pollution and GHG emissions	Kariada and Arsana (2019); Karim, Hifnalisa, and Manfarizah (2021); Mosquera et al. (2016); Golinucci et al. (2022)
Environmental: <i>Increasing biodiversity</i>	Improving the ecosystems services from coffee production	Haggar et al., 2021
Environmental/economic: <i>Increasing available nutrients</i>	Reduction of the costs of production	Chavez et al. (2021); Tully, Lawrence, and Scanlon (2012)
Economic: <i>Adapting to climate change</i>	Increasing farmers' resilience to unpredictable climate	Golinucci et al. (2022)
Economic/environmental: <i>Shade trees</i>	Better economic performance, mitigation of climate change impacts by reducing GHG emissions	Chatterjee et al. (2020); Jezeer et al. (2018); Méndez et al. (2009); Pronti and Coccia (2020)
Economic/environmental: <i>intercropping</i>	(1) Better economics and improved soil health (2) improve coffee quality for better prices (3) Diversified and higher income	(1) Bucagu, Vanlauwe, and Giller (2013); Sarmiento-Soler et al. (2020) (2) Golinucci et al. (2022) (3) Kuswadi and Fitriani (2021); Le et al. (2021); Golinucci et al. (2022)
Economic: <i>introduction of livestock</i>	Diversification of income for improved farmer resilience	Hasibuan, Ferry, and Wulandari (2022); Jezeer et al. (2018); Le et al. (2021); Martins Neto et al. (2020); Pronti and Coccia (2020); Thuy, Niem, and Lebailly (2020); Wulandari, Ferry, and Hasibuan (2022)
Economic: <i>Accessing new markets</i>	Higher incomes	Hasibuan, Ferry, and Wulandari (2022); Le et al. (2021); Rahmah et al. (2022)

understand what impact biochar can have on coffee productivity (Melaku et al. 2020).

Overall, the benefits for farmers, the farm environment or for the wider environment, or both, were mainly environmental, although there are also some environmental benefits that go together with potential economic benefits for farmers. These indicated a better economic performance regarding net income, improved resilience, higher coffee prices or higher yield (Table 4).

Articles on the environmental sustainability highlight a range of possible benefits

Eleven articles reviewed with an environmental or economic/environmental focus at a small scale (farm or smaller) recommended to some extent organic nutrient management, supporting the hypothesis. Overall, articles with an entire or partial environmental perspective were positive about the potential contribution that plant-derived additions can have (Figure 6(b)).

Le et al. (2021) compared soil samples taken from two conventionally managed, sun-grown Robusta coffee farms using inorganic fertilizers in Vietnam, with samples from an organic shade-grown system, and found that organic compost was as effective as chemical fertilizer at maintaining soil nitrogen, with no impact on available nitrogen but a significant increase in pH (4.1 under organic compared to 3.7 for conventional management), providing improved soil conditions for coffee production. Invertebrate abundance was also higher on the organic farm with no differences in bulk density, K and P concentrations, with organic management techniques leading to comparable or improved overall soil health.

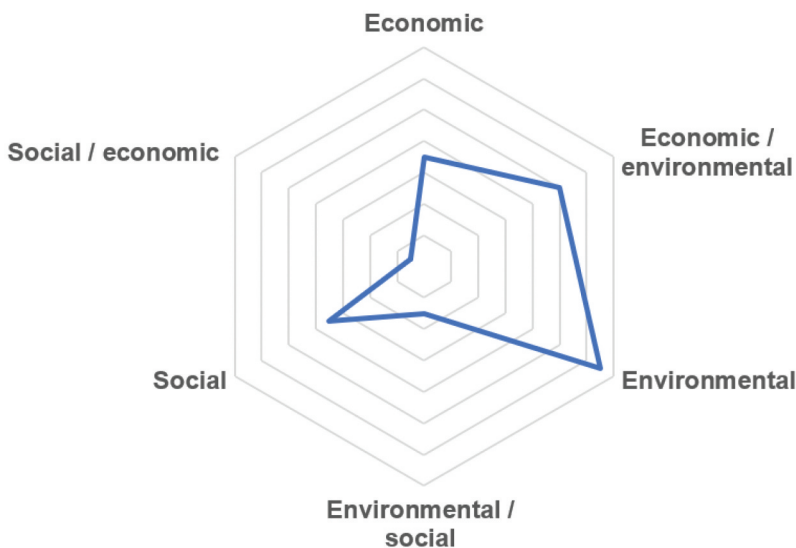


Figure 6. (a) Studies of different types of organic management; (b) categorisation of different practices with contrasting sustainability focus.

The relationship between organic inputs and soil health in general is supported by Kurniawan, Hariyanto, and Ishaq (2021) with organic fertilizer associated with 19–42% higher soil organic carbon concentrations compared to combining organic and inorganic fertilizers, with the likelihood that poorer soil organic carbon in conventionally managed systems are due to inorganic fertilizers breaking down organic matter faster, leading to a decrease in the soil itself. Results from Chatterjee et al. (2020) showed that the carbon sequestration potential of soil was higher under organically managed shade-grown coffee under agroforestry than under conventionally managed coffee. However, the results showed that conventionally managed coffee under *Terminalia amazonia* had the same carbon sequestration potential as organically managed coffee under *Erythrina poeppigiana* (a nitrogen fixing species), and results for sun-grown and conventionally managed *Erythrina* were also the same, emphasizing the importance of species selection in agroforestry system design, and consideration of both nitrogen, and carbon dynamics.

Martins Neto et al. (2020) found a combination of organic inputs improved soil characteristics; using a combination of the leguminous plant sunn hemp (*Crotalaria juncea*) as a green manure, along with compost, added sufficient nitrogen, counteracted the alkaline effect of compost alone and resulted in a better chemical balance in the soil overall, resulting in higher yields than using compost alone; higher doses of sunn hemp and compost is reported to have increased yields further. This is supported by Araujo et al. (2013) who found that adding sunn hemp along with organic compost improved the growth of coffee plants, compared to compost alone. Before flowering, there was no increased growth, but once the plant entered the reproductive phase with flowering and berry development, the sunn hemp contributed 9.2–17.9% of leaf nitrogen, although increasing the rates of organic compost above 7.5 g nitrogen/plant had no further positive correlation with increased yields.

Studies analyzing the impact of animal manure on soil health, nitrogen availability, and productivity again revealed environmental benefits (Fernandes et al. 2014; Wardani, Meidaliyantisyah, and Rivaie 2021). Fernando et al.'s (2019) study found that the proportion of soil organic matter (SOM) was higher where animal manure was used as an addition (4.4% SOM) or replacement (4.2% SOM) for inorganic fertilizer (3% SOM), while maintaining nitrogen. Le et al.'s (2021) study supports this, finding that nitrogen concentrations were similar (1888 ppm for farm with organic manure inputs, compared with 1942 ppm for the conventional farm). These findings contrast with other studies that found lower nitrogen concentrations in organic coffee cultivation (Méndez, Shapiro, and Gilbert 2009; van der Vossen, 2005, as cited in Le et al. 2021).

However, few studies recommended transitioning completely away from inorganic fertilizers, particularly where economic considerations were analyzed alongside environmental impacts. Fernandes et al. (2014) investigated

the impact of using coffee processing waste to reduce inorganic fertilizer use. This waste is made up of the skin, pulp and parchment separated from the coffee bean during processing (Haddade, Meneghelli, and Berilli 2019) and each 60 kg bag of coffee produced also produces 50–60 kg of coffee waste that can be used as an organic soil amendment. While using inorganic fertilizer increased yields over 5 years by 88–135% compared to the control, Haddade et al. found it was possible to reduce fertilizer application rates by 6–44% using coffee waste, with best yield results at 10,000 kg/ha, attributing the biomass gained as an effective approach for soil structure improvement, concluding that the organic addition was a feasible input to complement, rather than replace, inorganic fertilizer. Silva Araujo et al. (2014) came to a similar conclusion that leguminous jack-bean (*Canavalia ensiformis*), with the biomass of the plant added to coffee as a green manure, can replace some inorganic fertilizer and promote growth and development, as well as more than double the yield. Melaku et al. (2020) focused on the impact of biochar derived from coffee husks, finding that its application increased potential yields by up to 64% but to achieve this, there is a need to increase inorganic fertilizer application and use biochar produced at higher temperatures (500°C rather than 300°C) and applied at higher application rates (18t/ha rather than 6t/ha). Application, however, was shown to increase soil available phosphorus, and carbon content, providing wider potential soil health benefits. Precise impacts were, however, dependent on both fertilizer and biochar application rates, alongside production conditions

In many cases where articles focused on both environmental and economic aspects of particular management practices, even if the impact on coffee yields was included in the analysis (as in, for example, Karim, Hifnalisa, and Manfarizah 2021; Melaku et al. 2020; Nzeyimana et al. 2020; Thuy, Niem, and Lebailly 2020), the impact on costs of production or livelihood were omitted, making it hard to conclude the effectiveness of any given management practice for sustainable production based on yield alone, as highlighted by Jezeer et al. (2018). Conversely, articles that had a more economic focus tended to assess agroforestry and intercropping practices in the context of the use of shade trees and intercropping for their benefits for diversification of income (Sarmiento-Soler et al. 2020).

Articles focusing on economic aspects point to risks and trade-offs, particularly in transitioning

Profitability is a key driver of smallholder coffee farmers' decision-making, when it comes to management and management practices in general, as well as investment in coffee (Bravo-Monroy, Potts, and Tzanopoulos 2016; World Coffee Research 2021). Coffee yields in smallholder farms are much lower than their potential due to a variety of factors, including aging coffee trees,

increased prevalence of disease and unimproved genotypes with limited disease resistance, and declining soil health, amongst other factors (Chavez et al. 2021; Kudama, Wana, and Dangia 2021; Wang et al. 2015; Wardani, Meidaliyantisya, and Rivaie 2021). Yield provides only a partial picture when considering farmer livelihoods or farm profitability, ignoring the relative costs of inputs and labor related to yield (Jezeer et al. 2018), but it is still an important factor in consideration of strategies to increase return on investment (Bravo-Monroy, Potts, and Tzanopoulos 2016). Factors contributing to yield gap, and therefore influencing farmers' decisions about how to manage nutrients, include lack of capital to invest in replacing old coffee trees when yields decline (Hasibuan, Ferry, and Wulandari 2022), farmer knowledge of, and confidence about, trying new methods for increasing yields including improved nutrient management or agroecological approaches to enhance soil health (Kariada and Arsana 2019; Wardani, Meidaliyantisya, and Rivaie 2021), and lack of access to capital and labor for effective farm management (Kudama, Wana, and Dangia 2021). Yields may also be lower where local and national structures are not effectively supporting production, such as co-operatives, boards, and networks that share information. These can also increase farmers' bargaining power to negotiate better prices for inputs and coffee (Hasibuan, Ferry, and Wulandari 2022), and facilitate field education (Mulinde et al. 2019). It must also be the case that some smallholders, in response to the low and volatile price of coffee, put less effort and investment into their coffee than other livelihood activities (Golinucci et al. 2022).

Key to the discussion on risks and trade-offs is the transition from conventional to organic management and its impact on livelihoods. For instance, Le et al. (2021) points to several factors that may pose trade-offs for farmers including that transitioning can be labor-intensive, expensive, bring about a short-term increase in pests, reduce productivity in the short-term and can take time to establish. Transitioning to certified organic production involves using organic methods for 3 years before certification is granted, and assumes other requirements are met (e.g. those associated with pest management), with the transition window potentially locking farmers out of favorable price differentials for several growing season (Le et al. 2021), over a period during which yields are generally reduced (Bracken et al. 2022). Le et al. (2021) also found that, in the short-term, additional investment of \$4,350 in fixed costs for new equipment was required to purchase shade trees, cages and livestock to facilitate the transition. However, in the longer-term, the authors found that variable costs may reduce as the necessary infrastructure becomes self-sustaining, compensating farmers for any reduction of yield with improved productivity overall, as well as higher prices for better quality, organic coffee. Similarly, Jezeer et al. (2018) recommends transitioning, finding that overall, the economic performance of agroforestry systems is equally good or better than sun-grown coffee, or mineral-fertilized coffee, and that as inputs costs

such as fertilizer increase, transitioning may become more attractive, based on a study in Peru. Babin (2015) examined Costa Rican coffee farmers' responses to the "coffee crisis," which described the intersection of low coffee commodity prices and high input costs. Babin reported that Fair Trade price premiums had little effect on preventing land-use change away from coffee production. However, adopting shade-trees reduced reliance on expensive fertilizers through improvements to soil fertility and nutrient cycling, with these broad agroecological benefits enabling farmers to maintain coffee production more effectively under reduced agrochemical inputs.

More broadly, a growing body of literature (not specific to organic management) is emerging demonstrating how improvements in soil health (that could be mediated by organic or other agroecological interventions), can enhance coffee quality, which may bring economic benefits to farmers. Bote and Vos (2017) observed that bean quality attributes declined with increases in solar radiation when nitrogen supply was limited. However, in the absence of nitrogen limitation, measured quality attributes were largely insensitive to radiation levels. In full sun systems, there was no effect of nitrogen supply on either the size or weight of coffee beans, but nitrogen supply did enhance bean size and weight at lower solar radiation level. In a study in Colombia, Rekik et al. (2020) highlighted that farmers' perceptions of soil health were found to broadly match laboratory measurements of soil physicochemical properties from farms.

Pronti and Coccia (2020) found labor and input intensity was lower on Brazilian agroecological farms, with consequently much lower variable costs. While net income was lower, the profit per unit of land was higher; however, in modeled scenarios, where the market price farmers get for their coffee falls, farmers using conventional systems with a multi-product strategy are more resilient than agroecological farms more reliant on coffee. Transition is recommended alongside diversification.

Rahmah et al. (2022) recommend farmers transition to organic management based on the results of a Life Cycle Assessment (LCA) and Life Cycle Cost Analysis using data from Indonesia, identifying that coffee production with organic fertilizer management had a lower environmental impact but a higher energy cost than conventional (inorganic fertilizer) or mixed (inorganic and organic fertilizer) production methods; in this case due to the energy required to produce poultry manure. Basavalingaiah et al.'s (2022) study, using data from India and also based partially on LCA, reported similar results, with net GHG emissions 65% lower under organic production than for mixed or conventional production, attributed to the different approach to fertilizer, and implying that farmers can save money on input costs by transitioning to organic practices. Rahmah et al. (2022) also showed a higher economic return for organic systems, partly due to the higher price differential for organic coffee, for example through certification (Jones et al. 2024), although Le et al.

(2021) notes such benefits are likely to decline as more farmers transition to organic practices.

Without the resilience to manage a yield penalty, transitioning to organic management will continue to pose trade-offs. Transitioning can also involve moving from an intensive, sun-based, high input – high yield system, to a low-input – stabilized (but perhaps lower) yield system. This can suit smallholders who have limited access to credit and labor (Pronti and Coccia 2020) and may be more attractive for farmers who cannot afford inorganic fertilizers (Chavez et al. 2021), and as fertilizer costs rise exponentially (Perez 2022). This warrants more investigation, as fertilizer price rises may represent an opportunity to increase transition to organic management (Merrigan 2022; Perez 2022). However, in some countries, such as Vietnam and Uganda, a response to climate change-induced yield reduction has been to move to more intensive production to increase yields and protect income (Le et al. 2021; Mulinde et al. 2019), and some newer coffee varieties are developed for high-input-high yield systems (Basavalingaiah et al. 2022). Moreover, smallholders may find the low-input – stabilized yield system incapable of generating a living income on a small plot of land; larger farms can better distribute risk when trying new methods (Kudama, Wana, and Dangia 2021). It is also not clear if any benefits from reduced fertilizer costs may be offset by an increase in labor costs associated with increased farm management (e.g. pruning, planting shade trees) and the production of organic inputs on-farm (e.g. compost, manure) (Kudama, Wana, and Dangia 2021; Le et al. 2021), or whether agroecological practices in fact reduce labor costs (Jezeer et al. 2018; Pronti and Coccia 2020).

Intercropping and shade are recommended by all those studies focusing on them, particularly when they provide diversified incomes (Golinucci et al. 2022; Jezeer et al. 2018; Pronti and Coccia 2020). Even if coffee yields decline due to competition for soil nutrients, the extra income can improve livelihoods, for instance with bananas (Sarmiento-Soler et al. 2020); diversification with livestock could further reduce nutrient competition (Le et al. 2021). Intercropping with leguminous crops that generate income or contribute toward food security can bring together economic and environmental benefits and warrants longer term studies that examine the transition to this production method (Bracken et al. 2022), to develop recommendations for the right enabling environment with access to markets and post-harvest infrastructure for diversified production.

However, there is no one solution, and trials that focus on environmental and economic sustainability together, and taking social factors into account, are needed at a variety of levels to establish the right interventions at a local level before farmer adoption. While there is much evidence to support the

hypothesis that transitioning to a low input system with stabilized yields will improve farmers' resilience, much relies on the selection of species involved in any given locality from an environmental and economic perspective, as well as reducing reliance on coffee revenue, which fails to address a fundamental problem – low and volatile coffee prices. Involving farmers and prioritizing their needs throughout experimentation and participatory education is crucial (FAO 2022b; Guteta and Abegaz 2016) and examined further below.

Articles focusing on social aspects highlight barriers, but offer solutions

Several articles examined the drivers of farmers' decision-making in using agroecological techniques, including maximizing productivity, minimizing risk, stabilization of income and maintaining food security (Jezeer et al. 2019). The goal of reducing inorganic fertilizer has both global and on-farm implications, but it is individual farmers' decisions that will drive the changes that need to take place. Several articles found that farmers who have access to education and networks for information exchange can adopt practices that improve management, while where it is lacking, they are less likely to have the capacity or desire to make changes (Kudama, Wana, and Dangia 2021; Torres-Jiménez et al. 2020). Farmers are unlikely to adopt a new practice unless they are confident it will have a positive effect on profitability, even if there are environmental benefits of doing so (Kuswadi and Fitriani 2021; Le et al. 2021).

Several articles pointed to reasons why farmers choose not to adopt organic management, including age and experience. Wulandari, Ferry, and Hasibuan (2022) highlighted that older, more experienced farmers are less likely than younger farmers to use organic manure, with very low take-up despite an increasing demand for organic coffee. Le et al.'s (2021) study found that new, younger farmers in Vietnam were more likely to adopt sustainable soil management practices such as planting shade trees and eliminating inorganic fertilizers. However, Hasibuan, Ferry, and Wulandari (2022) found that there was statistical significance between the level of farmers' experience, and their likelihood to use more organic fertilizers. "Old" and "more experienced" are not interchangeable, and there is no straightforward relationship between either age or experience, when it comes to decision-making around organic management. In response to this finding, Wulandari, Ferry, and Hasibuan (2022) suggested access to low-interest credit, strengthening farmer institutions and introducing livestock onto farms to diversify income, whereas Hasibuan, Ferry, and Wulandari (2022) reported mixed coffee livestock farming as having the potential to reduce coffee production costs. This is one example of the complex mix of factors that influence farmers' decisions to adopt agroecological management practices. Thus, it can lead to different recommendations, when looked at from different perspectives – therefore,

there is no one strategy or solution for organic management that will fit a specific group of farmers even at a local scale.

Studies investigating the environmental benefits of organic management do not examine the impact on farmers' workloads or labor differentials. Including this aspect would provide a framework for farmers and agricultural institutions examining organic management to assess its feasibility on the ground. Organic compost and plant-derived additions are considerably heavier and bulkier than inorganic fertilizers, which raises the labor effort required to use them, and may present a barrier to adoption, particularly for smallholders and women farmers (Hartman 2020). Kuswadi and Fitriani (2021) noted that farmers are concerned with the perceived suitability and simplicity of coffee agroforestry techniques as well as productivity benefits, while Kudama, Wana, and Dangia (2021) concluded that farmers with larger plots may be less likely to adopt soil conservation techniques due to high labor needs inherent in them. Conversely, the same study noted that farmers with bigger plots may be more likely to experiment with new techniques in small areas to distribute risk, or to farm more extensively. Targeted measures to increase knowledge sharing and education for farmers in specific circumstances, such as soil management for those with bigger plots, are recommended.

Several articles highlighted the importance of field or agronomic education in adopting regenerative techniques, including organic management. They reported on the positive role that field education (Kudama, Wana, and Dangia 2021; Kuswadi and Fitriani 2021; Thuy, Niem, and Lebailly 2020) or peer-to-peer learning amongst farmers (Le et al. 2021) can have in encouraging farmers to adopt regenerative techniques, particularly where they can see that they have both economic and environmental benefit and will be realistic to implement on their farms. Torres-Jiménez et al. (2020) recommended formal environmental education to influence farmers' perceptions of new techniques – in this case using bat guano as a fertilizer. This article also asserted that local and national government is needed to improve the sustainability of coffee production, and with government providing subsidized inorganic fertilizer, farmers are unlikely to take on an untrusted, potentially labor-intensive strategy, even where there is evidence that organic management increases production and reduce pests.

Kudama, Wana, and Dangia (2021) pointed to the role that co-operatives have in field education in Ethiopia, finding that Fairtrade certified farmers – who, to be certified, must be members of a co-operative – were more likely to adopt certain regenerative practices. Jezeer et al. (2019) found that farmers who belong to a co-operative are more likely to adopt shade techniques, suggesting access to networks has an influence, although farmers' decisions about transitioning were heavily influenced by access to financial capital. Where farmers' own knowledge and perceptions are understood, participatory education for organic nutrient management can be enhanced, since farmers

have high knowledge and understanding of the conditions on their own farm which can be complemented with below-ground soil nutrient processes (Guteta and Abegaz 2016).

The role of general education in influencing farmers' decision-making to adopt new techniques is complex, and in all geographies, there is insufficient available data to link education directly to the adoption of a wide suite of practices. Evidence primarily relies on studies focussed on individual communities or co-operatives, and a limited subset of practices often with local variation, and thus making generalizations or identifying broad trends is not feasible. For example, Kudama, Wana, and Dangia (2021) found that farmers in Ethiopia with a higher education level invest less in their coffee, Yushmani et al. (2020) found no significant correlation between education levels in Indonesia and productivity. Torres-Jiménez et al. (2020) found a correlation between lower education levels and hesitancy or fear about using bat guano fertilizer amongst farmers in Mexico. Conversely, Jezeer et al. (2019) found that education and wealth correlated with the adoption of more practices to protect the environment amongst farmers in Peru. The level of education amongst farmers in Uganda was also found to positively influence their adoption of specific practices around intercropping for diversification of income. Farmers with more years of education were better able to identify when rainy seasons were starting and ending, and also tended to prioritize expert knowledge when adapting practice (Mulinde et al. 2019).

Transitioning to organic management requires experimentation to establish which combination of methods will suit the soil, climate, and ecology of a coffee farm, as well as labor and technical factors (Le et al. (2021)). In a study in Vietnam, Le et al. (2021) highlighted the importance of the pioneering farmer who is willing to experiment with transitioning on some or all of their land; many of their neighboring farmers will look to this and wait to see the results before making their own decision. What is clear is that there are barriers to the adoption of organic management techniques by coffee farmers, and many of these barriers relate to factors associated with social aspects of sustainable development. High levels of inorganic fertilizer are still promoted and supported at a political level in some countries, such as Vietnam and Mexico (Le et al. 2021; Torres-Jiménez et al. 2020). In Uganda, government policy has encouraged use of inorganic fertilizers as an adaptation to climate-induced yield reductions (Mulinde et al. 2019), while in Kenya co-operatives have discouraged farmers from intercropping (Wairegi et al. 2018), which research shows can help build farmers' resilience by providing a more diverse income base and improving soil health (Golinucci et al. 2022; Sarmiento-Soler et al. 2020). Conversely, farmers in other coffee-producing countries such as Ecuador and Ethiopia, where inorganic fertilizers are less used but agroecological techniques are not yet widespread, experience a huge yield gap as they

lack access to labor or field education (Chavez et al. 2021; Kudama, Wana, and Dangia 2021).

in Ethiopia, Kudama, Wana, and Dangia (2021) reported that Fairtrade and other certification schemes can help encourage the adoption of organic management practices, alongside other approaches such as enhanced pest management, through providing a longer-term financial incentive, while Jezeer et al. (2018), Le et al. (2021) and Thuy, Niem, and Lebailly (2020) noted that sustainability certification also led to increased profitability. In Kenya, farmers have been encouraged to enhance coffee production through Fairtrade and Rainforest Alliance certification, with access to credit for inputs (Wairegi et al. 2018). However, Wairegi et al. (2018) noted this has not been successful and suggested a more targeted approach to training, credit, and support based on age and experience of farmers. While older farmers are less able to intensify production with management practices because of a variety of factors including poor prices, lack of training and comparative frailty, younger farmers rely on coffee less for income and tend to diversify, but lack access to credit to improve their production to raise yields. However, the authors also found farmer support and networks do not uniformly create an enabling environment for organic management through agroecological techniques. In a study in Agua Buena, Costa Rica, Babin (2014) found that Fair Trade price premiums did not impact rates of land use change out of coffee production, but that agroecological techniques (including diversification through the incorporation of shade trees) were beneficial through reduced external inputs maintaining productivity.

Interdisciplinary research that integrates the three pillars of sustainable development is lacking

No articles were identified which considered the combined social, economic, and environmental aspects of sustainable coffee production at anything more than a superficial level. These three aspects of sustainability contain a wide range of elements that are interrelated (Gibson 2006) (Figure 1) and should all be accounted for in any study that is to be of practical application to farmers. The lack of integration across aspects of sustainability means that research needs adapting in order to have an impact in smallholder contexts (Stanbury 2020). Changes to production methods that ignore the economic aspect in particular will not be adopted; farmers will choose methods that are primarily economically and environmentally sustainable (Rahmah et al. 2022). Smallholders struggling to make a living income from their farm are unlikely to take on more risk by adopting new practices; smallholders tend to be cautious about adopting new methods because they do not have the physical space or financial resources to experiment and fail (Stanbury 2020).

The risks and barriers to organic management for coffee farmers are not obviously overcome by the opportunities and benefits, so that a straightforward decision cannot easily be made by farmers. Most of the factors preventing farmers from reducing or eliminating inorganic fertilizers relate to coffee prices, a lack of capital, and a lack of knowledge and support. However, the factors that could push them toward regenerative agricultural practices do not yet clearly demonstrate economic benefits or sit within a coherent enabling environment. While all articles in review show high benefits from organic management for improving soil health, productivity, reducing environmental degradation and/or reducing the use of inorganic fertilizers, no studies are able to clearly demonstrate that the transition to entirely organic methods reliably enables farmers to maintain or increase yields while maintaining or reducing their input costs, even if transitioning to organic management practices alongside broader adoption of other approaches (e.g. for pest management) creates opportunities for farmers through organic certification which in turn can create new market opportunities and mitigate to some extent against low and volatile prices (Hasibuan, Ferry, and Wulandari 2022; Le et al. 2021; Rahmah et al. 2022).

Conclusions

There is extensive evidence to support the hypothesis that transitioning from a high input system to a low input system, substituting inorganic fertilizers for a range of management techniques that make use of available organic nutrients, will improve farmers' resilience. However, there is no clear pathway, and risks and barriers exist particularly in transitioning. At the heart of this is farmer decision-making about the risks, and trade-offs in organic management based on economic and environmental issues. Farmers are also influenced by a range of social factors in their decision-making and need a coherent local and national enabling environment that promotes policies and education that supports transition, and this is not always the case. In response to this, research that considers the negative trade-offs and co-benefits of organic management by firstly conducting scientific experiments that show what works to improve soil health, adapt to and mitigate for climate change and improve biodiversity, and then expanded in the context of coffee production to analyze how they impact profitability, are needed. These should then be integrated with studies that take into consideration the decision-making drivers and steps that policy makers and farmers' groups can take to create an enabling environment for organic management. This more systematic approach could be more effective in not only influencing behavior but also ensure progress toward sustainable farming.

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