Which diversification trajectories make coffee farming more sustainable?

Valérie Poncet, Piet van Asten, Claude P Millet, Philippe Vaast, Clémentine Allinne

Available online at www.sciencedirect.com

ScienceDirect

Current Opinion in Environmental Sustainability

Review

Which diversification trajectories make coffee farming more sustainable?

Valérie Poncet[1], Piet van Asten[2], Claude P Millet[1,3,4,5,9], Philippe Vaast[6] and Clémentine Allinne[7,8]

Annual global coffee consumption growth (1–2%) has been largely met (> 50%) mainly by Brazil and Vietnam through high-input monocrop system adoption. Smallholders account for > 80% of global producers and > 60% of global supply despite limited farm sizes (< 2 ha), yields, and input usage. Production concentration in areas with high-yielding systems has fulfilled global demand growth while keeping coffee prices low. However, climate shocks demonstrate the vulnerability of all supply models, strengthening the voice of those advocating more resilient and diversified systems. We review current agroforestry knowledge to identify key trade-offs and synergies between sustainability/performance indicators (i.e. economic, environmental, and social) and explore pathways for a more sustainable coffee future with three examples representative of global coffee production system diversity.

Addresses
[1] DIADE, Univ Montpellier, IRD, CIRAD, Montpellier, France
[2] OLam Food Ingredients (ofi), Singapore, Singapore
[3] CIRAD, UMR ABSys, Montpellier, France
[4] ABSys, Univ Montpellier, CIRAD, INRA, Institut Agro, Montpellier, France
[5] Quisqueya University, Port-au-Prince, Haiti
[6] UMR Eco & Sols, CIRAD, Univ Montpellier, Montpellier, France
[7] GECO, Univ Montpellier, CIRAD, Montpellier, France
[8] CIRAD, UPR GECO, Montpellier, France
[9] CIRAD, UMR DIADE, Montpellier, France

Corresponding author: Valérie, Poncet (Valerie.poncet@ird.fr)

Current Opinion in Environmental Sustainability 2024, **68**:101432

This review comes from a themed issue on **Sustainable Food Systems**

Edited by **Maria J. Darias, Mafaniso Hara, Israel Navarrete** and **Eric O. Verger**

Available online 14 March 2024

Received: 24 February 2023; Revised: 10 February 2024; Accepted: 15 February 2024

https://doi.org/10.1016/j.cosust.2024.101432

Introduction

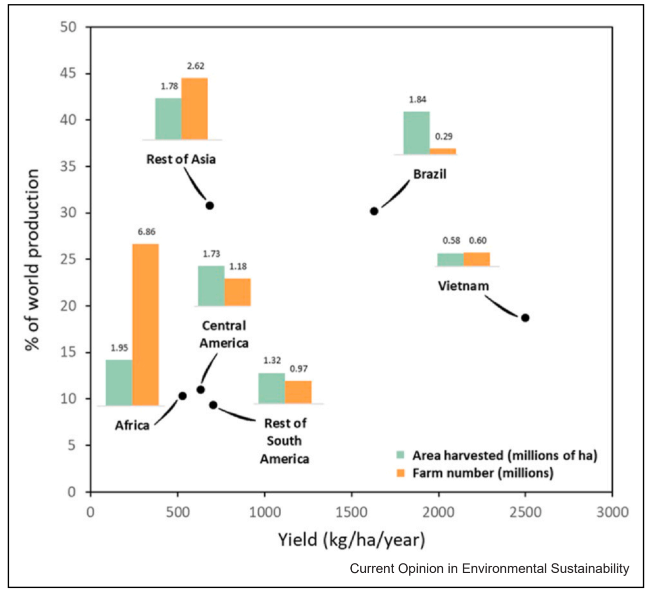
Global coffee consumption is expected to increase by 1–2% a year through the end of the decade [1]. Coffee will therefore remain essential for rural economies of developing countries in the humid tropics where it is grown. Indeed, the industry is estimated to support the livelihoods of over 12 million farming families worldwide. As such, it has the potential to directly contribute to fulfilling the UN Sustainable Development Goals (SDGs) 1 ('no poverty') and 8 ('decent work and economic growth') [2], although this is not yet been attained everywhere, as 44% of world coffee farmers still live in poverty and 22% live in extreme poverty [3]. However, coffee-growing landscapes are increasingly impacted by environmental degradation and climate change [4]. In response, a growing number of public and private sector actors advocate 'regenerative' and 'sustainable' agriculture. Sustainability frameworks that define these concepts align on (1) environmental, (2) economic, and (3) social pillars. The interdependency of these sustainability pillars was also recognized by the Global Biodiversity Framework at the 15th meeting of the Conference of the Parties (COP15, target 10 [5]).

Coffee trees have evolved as understory shrubs in carbon-rich and biodiverse rainforests [6]. When coffee systems partially mimic this pattern by incorporating agroforestry practices, they contribute to climate mitigation and biodiversity conservation, which play a major role in further fulfilling SDGs 13 ('climate action') and 15 ('life and land') [2,7]. Diversifying coffee cropping systems through the adoption of intercropping and agroforestry practices, such as the use of multipurpose shade trees, increases biodiversity and the resilience of the system [8]. Indeed, if we define resilience as the ability to anticipate, absorb, accommodate, or recover from climate and market shocks [9], growing a diverse range of agricultural products (feed, food, and wood) improves system resilience by generating value alongside coffee [10]. This enhances livelihood and income diversification and the ability to adapt to price fluctuations, climate variability, and pests and diseases [11].

However, it is impossible to provide a universal, 'one-size-fits-all' approach to incorporating agroforestry practices into coffee production, as their success highly depends on the farmer's situation and the environmental setting. The stereotype of dedicated smallholders nurturing shade-grown coffee on the steep slopes of lush tropical highlands has been carefully crafted by producer countries and coffee roasters for marketing purposes. In reality, the trend in many countries has so far been toward coffee production intensification with increased chemical inputs [4,12]. Consequently, these systems are currently hampered by soil health issues, such as acidification and the presence of nematodes and fungal pests. Low levels of above-ground plant diversity also reduce the presence of natural pest predators and parasitoids while increasing pest (e.g. leaf miners and borers) and disease pressure, thereby creating stronger pesticide dependency [13,14]. There is therefore considerable scope for improving coffee production sustainability. This raises the following questions: How can coffee production systems be made more sustainable by taking the diversity of production situations into account, and how can coffee system diversification address different challenges according to the context?

To explore potential trajectories to achieve more sustainable coffee cultivation in a changing climate setting, we must first understand the constraints and needs of coffee farmers in their local context in order to be able to propose tailored improvements. In this article, we take stock of current knowledge to describe coffee production systems worldwide, examine how climate change is likely to affect them, the role that diversification can play in their resilience, and, finally, how to improve their sustainability. The challenges of diversification through agroforestry for each major type of system will be presented using representative examples. For this, we will look at three contrasting coffee-growing areas in (1) Brazil, that is, large-scale high-yielding monocropped Arabica, (2) Vietnam, that is, small-scale high-yielding monocropped Robusta, and (3) Ethiopia, that is, small-scale low-yielding and shade-grown Arabica, and illustrate how different systems require different pathways to transition to more resilient coffee systems.

Figure 1



Representation of the main coffee-producing regions (Arabica and Robusta included) according to their productivity (average yield per hectare) and their world production contribution (expressed as a percentage of world production). The harvested area and the number of farms in each region are specified by barplots. The countries considered are Brazil and Vietnam as the most productive countries; Ethiopia, Kenya, Uganda, Rwanda, Burundi, United Republic of Tanzania, Cameroon, and Togo for Africa; Laos, Indonesia, and China for the rest of Asia; Mexico, Guatemala, El Salvador, Honduras, Nicaragua, and Costa Rica for Central America; and Colombia, Ecuador, and Peru for the rest of South America. Data
Source: ITC -Enveritas [13] and FAO [14].

Worldwide heterogeneity of coffee systems

Coffee is cultivated in over 70 countries throughout the tropics, with *Coffea arabica* (Arabica coffee) accounting for approximately 60% of global production and the remaining 40% being *Coffea canephora* (Robusta coffee) [15]. While both small- and large-scale farms are present in all countries, their relative importance to the coffee-growing sector varies by country.

Smallholder farmers (< 5 ha) represent 95% of world coffee farmers and produce most of the world's coffee [3], with estimates ranging from 60% [16] to 80% [12], despite modest yield levels (typically 500–1000 kg/ha/year of green coffee beans) and low to moderate use of external inputs [12] (Figure 1). The remaining production comes from larger farms (> 5 ha), with less than 1% being greater than 20 ha [12] but characterized by high fertilizer input levels (> 500 kg/ha), low to no shade tree density, and high average green bean yields (> 1.5 t/ha). However, these intensive practices are also implemented on small surface areas, as in Vietnam.

Indeed, two countries alone account for almost half of global production, with Brazil and Vietnam, representing 30% and 19% of world production, respectively (Figure 1). These countries rely on considerably different production strategies. Brazilian coffee farms are typically large, highly productive (on average: 6.4 ha; 1660 kg/ha), and managed by a small number of farmers (< 0.3 million farmers with only 14% having > 20 ha; Figure 1), whereas in Vietnam, coffee farms are small, numerous, and extremely productive (on average: 1 ha; 2500 kg/ha).

Other coffee-producing regions (rest of Asia, Central America, rest of South America, and Africa) have yields averaging no more than 700 kg/ha, with farm areas of around 1.4 ha in America, 0.7 ha in the rest of Asia, and only 0.3 ha in Africa (Figure 1). For instance, very small farms (< 2 ha) prevail in Ethiopia (2.2 million), Uganda (1.8 million), and Indonesia (1.3 million; Figure 1).

The historical and present specificities of each country's agricultural system (i.e. land use, farmer's motivation, planting age, management intensity, support from technical institutions, public policies) explain the diversity of coffee production scenarios currently observed across the globe. Considering this heterogeneity of systems and contexts, the key questions to be addressed to find the best trajectory toward sustainability are as follows: (1) how can intensive systems be made environmentally sustainable while maintaining profitability and reducing risk?; and (2) How can traditional systems be made economically profitable and socially fair without reducing the ecosystem services they provide? These concerns must be considered in the global context of climate change, which is the main challenge facing coffee production in the next 30 years.

The impact of climate and market volatility on coffee systems

Coffee production has doubled over the last 30 years, amounting to > 169 million bags in 2018 [15]. To meet growing global demand [15], major producers (namely, Brazil and Vietnam) enhanced the productivity (yield per hectare) of existing coffee fields, whereas many other countries increased production by expanding the land area under coffee cultivation. This latter strategy had significant socioeconomic and environmental consequences due to the resulting deforestation [17] and the reduction in food self-sufficiency since smallholders allocated a larger share of their farmland to coffee [11]. Agricultural area expansion is the main driver of natural vegetation loss, particularly in the tropics, and it threatens more than 19 of the currently recognized 36 global biodiversity hotspots [18]. For example, the Central Highlands of Vietnam saw a 13.5% decrease in natural forest area between 1995 and 2010 due to agricultural expansion, including coffee farming [19]. Over the 2001–2015 period, coffee accounted for 1.62% (2 million hectares) of all agriculture-linked deforestation worldwide (123 million hectares), behind livestock grazing, oil palm, and soy cropping [17]. Deforestation and forest degradation are major drivers of climate change and biodiversity loss. To slow down this trend, the European Union Deforestation-Free Regulation entered into application in May 2023 [20], requiring importers of commodities such as coffee to certify that their products are not associated with deforestation occurring after December 31, 2020. With Europe importing more than one-third of global coffee production, the International Coffee Organization has stated that it is seeking to ensure the sector is prepared for new regulations [21].

Despite the increased demand, market imbalances and asymmetric value distribution among market stakeholders impact the livelihood of millions of smallholder producers [15]. Coffee has seen recurring boom and bust cycles, and there have been 10 troughs for coffee prices since 1970, mostly associated with weather-related supply shocks in the major producing countries [22]. In particular, drought and frost events in Brazil (induced by La Niña) and drought in Central America (induced by El Niño) have caused global coffee price surges, resulting in an expansion in the production area and subsequent overproduction, in turn leading to busts in later years. Recently, recurring droughts and frost have hit Brazil in 2019–2022, once again sharply increasing coffee prices [22]. Another type of supply chain shock occurred in early 2020, when the world was fettered by the coronavirus disease 2019 pandemic, which impacted labor availability and (local) input/output markets [23].

Climate change is expected to exacerbate the existing vulnerabilities and create new ones, forcing many smallholders into alternative livelihoods [24]. Coffee-based farming systems are among those already showing signs of climate vulnerability. The predicted impact of climate change on coffee is large and well documented [25]. The majority of current literature suggests that climate change and drought have predominantly negative effects on coffee production. Climate change is projected to cause substantial reductions in the areas suitable for coffee production by 2050 [26], with large areas of major coffee producers such as Brazil and Vietnam becoming less suitable or unsuitable [27]. Some higher elevation and latitude areas which are currently suboptimal for coffee may become more suitable [6,26] but will require geographical shifts in coffee production. Coffee is impacted by increasing drought events [28], temperature, and outbreaks of pests and diseases, such as coffee berry borers (*Hypothenemus hampei* [Ferrari]) [29], coffee leaf rust (*Hemileia vastatrix* [B & Br])[30], and coffee white stem borers (*Monochamus leuconotus* P.) [31]. Coffee yield and quality are also predicted to decrease due to negative impacts on flowering [32,33], fruiting, and bean quality [28,34]. However, positive effects of climate change on coffee production are also reported [25], including increased suitability in higher elevation regions, greater pollination activities [35], and higher carbon concentration, enhancing photosynthesis and heat tolerance, thus improving crop growth [36]. Nevertheless, the balance between positive and negative effects has not been quantified, and these changes could be expected to mainly affect the most economically vulnerable producers. Climate change and shocks will particularly challenge smallholder farmers, many of whom are dependent on rainfed cultivation, have limited access to financial and technical services (e.g. integrated pest management, improved varieties), and often lack economic alternatives.

What practices can improve the system over time and space

While coffee farmer needs for climate change adaptation strategies are pressing, applying such strategies can take many years to take effect in tree cropping systems. While a coffee field requires between 3 and 5 years to reach economic yields, its lifespan can reach 30 years or more. Furthermore, in the case of agroforestry systems, it can also take more than 5 years for associated shade trees to mature and benefit the coffee crop. Thus, decisions to implement adaptation strategies are complicated by the need to consider large timescales, especially in the case of agroforestry systems.

Adaptation measures aimed at minimizing the exposure and vulnerability of coffee crop systems can be implemented at different levels [37]. For coffee systems to be resilient and regenerative, the choice of strategies must be based on a clear understanding of functional interactions between the adoption of field-based practices and landscape benefits. For example, Schmidt and Bunn [38] reviewed climate-smart practices in coffee farming and classified the benefits into seven functional groups focused on soil characteristics, water management, crop and genetic diversity, climate buffer and adjustment, crop nutrient management, structural elements and natural habitats, and system functioning. Based on these functional benefits, adaptation practices implemented in coffee fields and described in the literature primarily revolve around (1) agroforestry, (2) intercropping, (3) irrigation and water conservation, (4) soil fertility management, and (5) planting of high-performing cultivars that are drought and pest/disease tolerant. In addition, farmers can improve their livelihood resilience through diversification of agricultural enterprises (i.e. crops, livestock, aquaculture) or by boosting their off-farm income through employment or casual labor.

In general, the diversification of crop systems through the adoption of intercropping and agroforestry practices generally promotes higher ecological resilience and biodiversity conservation to cope with climate change but also smallholder livelihood resilience through improved food security and reduced sensitivity to market volatility [39].

Positive impacts of diversification

Enhancing biodiversity by cropping system diversification has positive effects on the overall dimension of sustainability (environmental, social, and economic), and the effects are variable depending on the cropping system [40] (Figure 2). In the highly productive Brazilian and Asian systems (1500–2500 kg/ha/yr), diversification has positive impacts mainly on ecological indicators of sustainability (ecosystem services, biodiversity, and pesticide load). In many parts of Latin America and Africa, where average yields are lower (< 1000 kg/ha/yr), diversification has a further positive effect on socioeconomic indicators (economic resilience, market value, economic value of ecosystem services, variety and value of products consumed by householders; Figure 2). Positive effects of diversification on resilience — defined as the capacity of farming systems to resist, recover, and adapt to disturbances over time — have mainly been reported for Africa [40]. Teixeira et al. [40], however, highlighted the fact that many studies on diversification focus on biodiversity- and ecosystem-based indicators (yet these are still underreported) while overlooking socioeconomic- and resilience-focused indicators.

Above all, there is a need to propose pathways for transition toward system diversification and enhanced sustainability adapted to the local context [41]. In the case of large intensified farms, efforts toward greater sustainability must focus on reducing negative environmental impacts, such as loss of soil health, biodiversity erosion, and pollution of water bodies, while maintaining profitability. In the case of smallholders, sustainability strategies must focus first on economic profitability improvement, livelihood strengthening, and food security. Even if minimal, these changes will have significant large-scale impacts (Figure 2). A broad range of production systems prevail between these highly contrasted scenarios, such as intensive smallholder cropping systems, which feature both over- and under-use of agronomic inputs and practices, and this aspect has yet to be sufficiently documented to date.

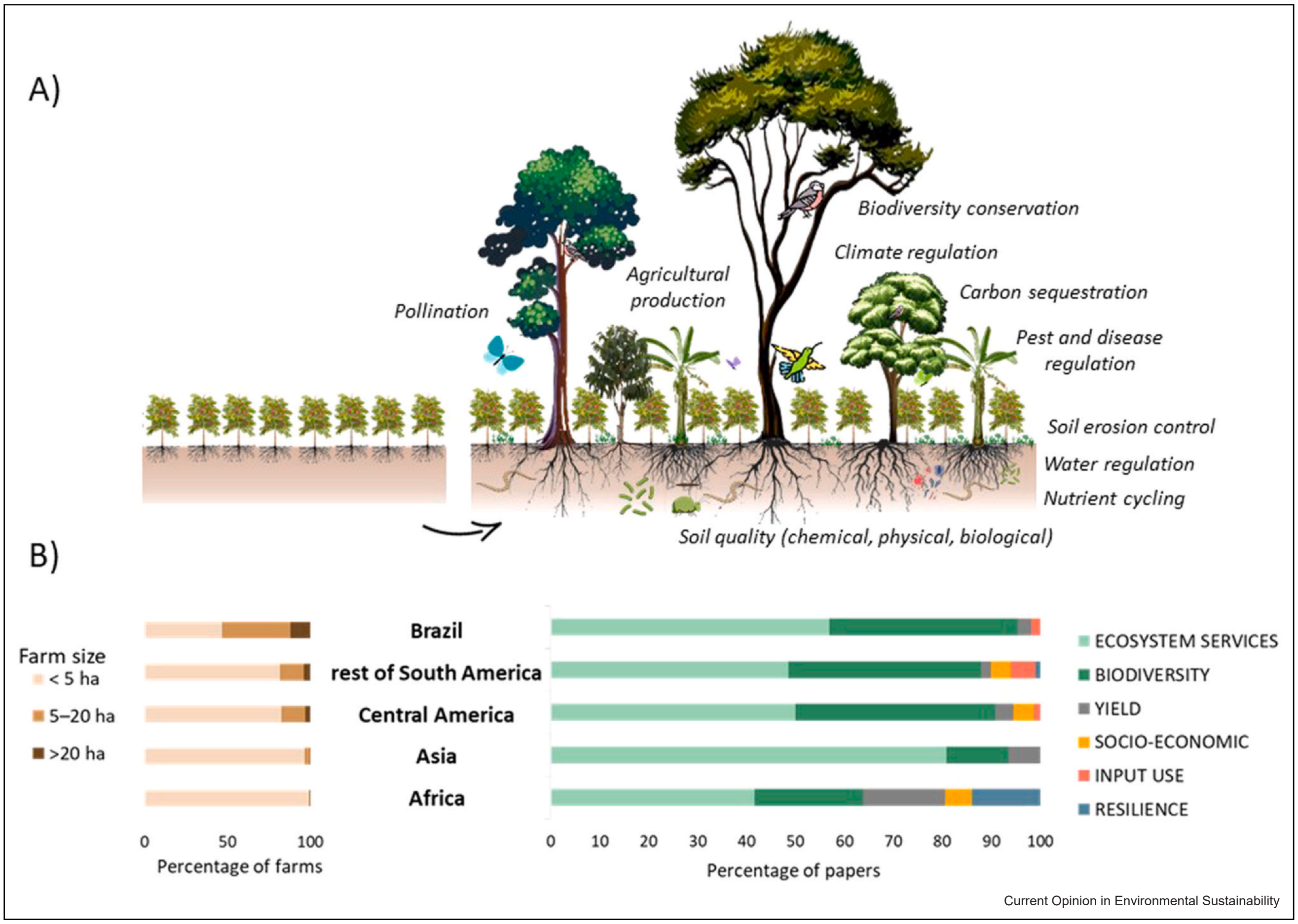
System-specific challenges and the need for appropriate responses: case studies in three important examples

The transition toward more sustainable systems through appropriate biodiversity management (organization and structure) must aim to reduce any trade-offs that may arise when striving to maximize both economic output and system resilience through diversification. For example, there can be a negative relationship between yield and biodiversity (plant species richness and composition) in coffee agroforestry systems [42]. Here, we explore three contrasting examples to illustrate the substantial gradient in coffee production systems in terms of composition and structure (monospecific vs traditional polyculture) and farming system (commercial vs smallholder farms; Figure 3).

Example 1: commercial farm transitions in Brazil

Brazil is the world's largest coffee producer, with a 30% market share (Figure 1). The coffee production chain there is responsible for generating more than 8 million jobs, including 287,000 coffee growers. Brazil is the only country where the average coffee producer earns a net income that is above some living income estimates (defined as the net income guaranteeing a decent standard of living) [43]. In most cultivated areas of Brazil (especially the state of Minas

Figure 2



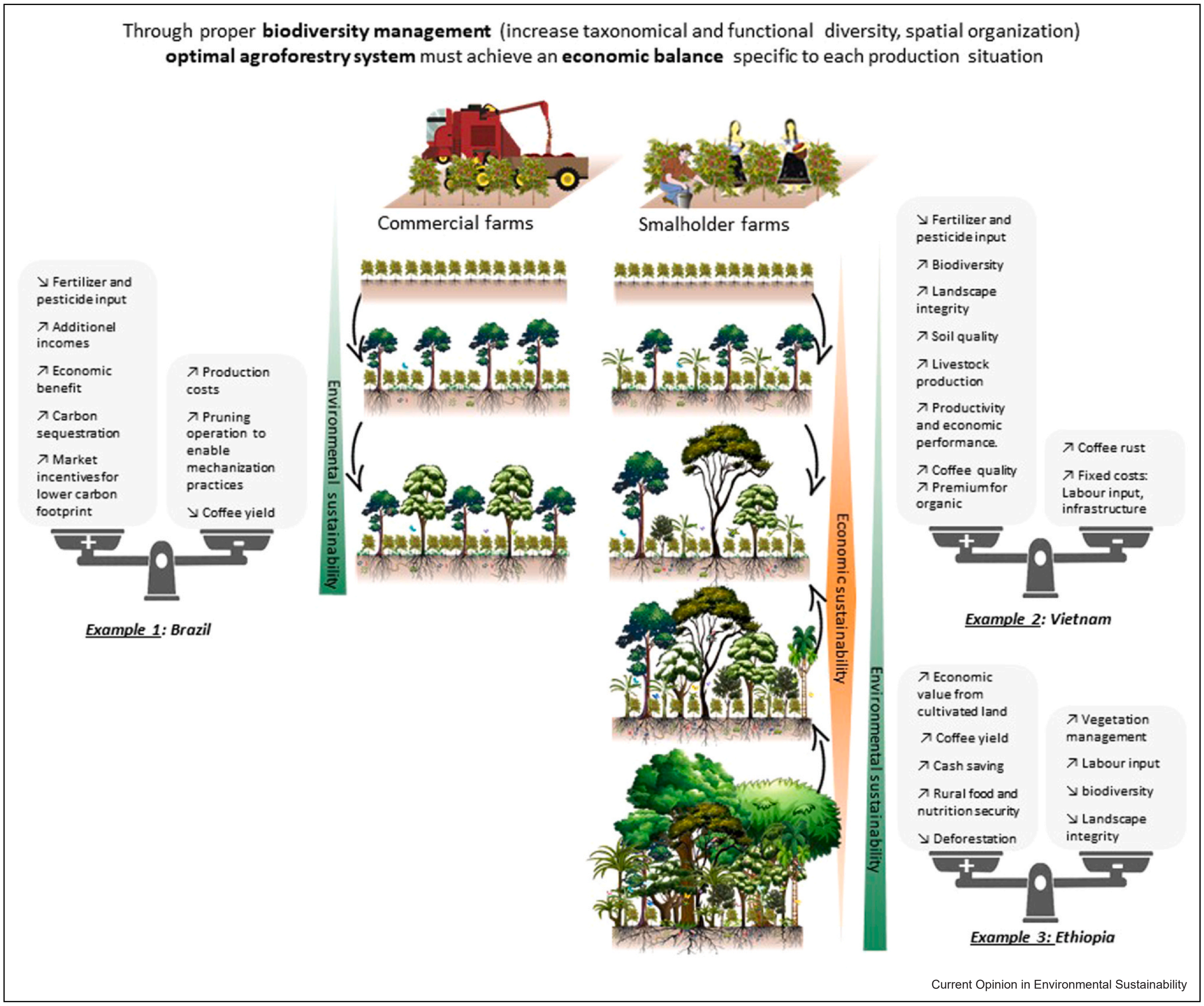
Positive effects of coffee diversification through agroforestry on ecosystem service provision **(a)** and on sustainability indicators in Brazil, Asia, rest of South America, Africa, and Central America **(b)**. Main ecosystem services provided by diversification are mentioned in italics, and farm size distribution is specified for each region.
Adapted from Texeira et al. [40].

Gerais), coffee is grown in an intensive, high-input system and under full sun. Many larger farms are vertically integrated — growing, processing, and exporting their coffee — and have made significant capital investments in technologies such as modern irrigation methods and mechanized harvesting to lower their production costs [43]. However, the dominance of unshaded coffee systems makes coffee production in Brazil vulnerable to climate change impacts, with serious potential socioeconomic repercussions. Furthermore, the use of pesticides as the most common measure for controlling coffee pests has a major negative environmental impact.

It is estimated that in the main coffee-growing states of Minas Gerais and São Paulo, the proportion of land suitable for coffee farming could plummet from 70–75% to a mere 20–25% by the 2050s [26], and the potential yield could be reduced by about 25% by the end of the 21st century [34]. In the Southeast Mountains, another major coffee-producing region, Gomes et al. [44] predicted that by 2050, the annual mean air temperature will increase by 1.7°C, leading to an almost 60% reduction in growing areas suitable for unshaded Arabica coffee production. However, they also provided an insightful example of the role of biophysical modeling to gain a better understanding on how agroforestry with different levels of shade tree cover could enhance climate change adaptation. Agroforestry systems with 50% shade cover could mitigate these impacts by reducing mean air temperatures while maintaining 75% of the area suitable for coffee production, particularly between 600 and 800 m elevation [44].

In addition to addressing the climate change challenges, the implementation of agroforestry practices in Brazil would also enhance field biodiversity and reduce

Figure 3



Transition pathways of coffee systems toward sustainable agroforestry cropping systems according to their initial production situation (monoculture vs traditional polyculture; large commercial vs smallholder farms). Positive (+) and negative (–) impacts of diversification to be considered to strike a sustainable balance are summarized for the three examples detailed in the text.

reliance on pesticides (Figure 2). Current strategies pursue these objectives while also aiming to maintain mechanization practices and ensure a profitable venture for farmers (Figure 3). Typically, diversification approaches involve the intercropping of cash crop trees, such as the native macauba palm (*Acrocomia aculeata*) [45], rubber trees (*Hevea brasiliensis*) [46], and macadamia (*Macadamia integrifolia*) [47], which generate an economic return. Indeed, this economic aspect is crucial for the success of a system transition in Brazil, where production costs have increased over the past years due to rising input and labor costs. While a study found that coffee monoculture can yield 2443 kg/ha in Minas Gerais, a much lower yield was reported for agroforestry systems, that is, 515 kg/ha [48]. However, a current example of successful Arabica coffee–macadamia intercropping illustrates the possibility of maintaining mechanized cropping practices and achieving an economic benefit 178% higher than that which may be achieved by coffee monocultures [47], thereby mitigating the trade-off between increased sustainability and yield. Alternative agroecological strategies aimed at improving field biodiversity and reducing pesticide use have also been proposed, such as (1) alternate row mowing, (2) planting mixed cover crops (e.g. legumes × grass species), and (3) planting tree species with extrafloral nectaries (e.g. *Senna* spp., *Inga* spp.) [49], which are then kept at limited height (< 3 m) to allow continued use of overhead pivot irrigation and mechanized harvesting. All these practices increase field biodiversity and allow natural predators (e.g. wasps, ladybugs, lacewings) to control insect pests and disease vectors [50].

There are many challenges along the pathway to adapting the Brazilian coffee chain to climate change and making production more resilient. This transition is crucial considering its high status on national and international markets, and it can only be achieved if there is no loss in economic benefits and livelihoods (in keeping with SDGs 1 — 'no poverty' and 8 — 'decent work and economic growth'). However, some agroecological strategies based on plant diversification and optimized management would be suitable for Brazilian coffee cultivation so as to meet the ergonomic needs of mechanized systems in areas with high labor costs and/or limited labor availability. Implementing these strategies could help align Brazilian coffee cropping systems with other UN SDGs such as SDGs 12 — 'responsible consumption and production', 13 — 'climate action', and 15 — 'life and land' (Figure 3).

Example 2: smallholder intensive coffee monoculture transitions in Vietnam

Vietnam is the largest producer and exporter of Robusta coffee on the global market, ahead of Brazil and Indonesia [15]. Vietnam has developed a high-intensity approach to Robusta coffee cultivation, boosting farmer profitability through irrigation, substantial chemical fertilizer use, pruning practices, and the planting of high-yield elite varieties [15,51]. Since the 1990s, the plantation area has expanded at the expense of the environment in Vietnam's Central Highland region. Vietnamese coffee production predominantly takes place on small, mostly family-owned (and run) coffee farms dispersed over a large area. As a result of these accumulated practices, the Vietnamese coffee industry is now facing several challenges — aging coffee trees, fragmented production, and the effects of climate change on widespread coffee monocultures. The Central Highlands — the main Robusta-growing region — are predicted to be especially affected by climate change, with expected reductions in land suitable for coffee farming [52] and potentially in yields [27].

However, in this region, some farmers are already converting their conventional full sun farms to organic shade farms while implementing regenerative farming techniques for both environmental and economic reasons [53]. Regenerative farming practices in smallholder plantations could successfully facilitate the transition from intensive conventional monoculture systems toward commercial polyculture systems, with the introduction of profitable fruit trees such as durian (*Durio spp.*) [53]. In Lam Dong province in the Central Highlands, the effects of regenerative practices have been ecologically and economically assessed at the farm scale in comparison with conventional systems [53]. Agroforestry practices can be evaluated in terms of the way they address regenerative agriculture's five core environmental concerns, as proposed by Elevitch et al. [54]: soil fertility and health, water quality, biodiversity, ecosystem health, and carbon sequestration. Regenerative farming practices in Lam Dong province consist of integrating coffee with shade trees (for timber and/or fruit self-consumption) and other crops (rice and food crops), avoiding chemical fertilizer or pesticide use, enhancing soil quality, promoting biodiversity, and improving productivity and economic performance. However, observed increases in coffee rust incidence, which is favored by microclimatic conditions that prevail in shaded conditions, highlight the trade-offs that can arise as a result of the complex interactions between pests and diseases, yield, and other ecosystem services in diversified agroforestry systems [55,56]. While developing production systems with reduced and more rational use of chemical inputs (i.e. fertilizers, pesticides) seems an essential step, the zero chemical input goal seems highly ambitious, given the potential increase in pressure from some pests and diseases. Chemical input reductions must therefore be pursued while maintaining the balance between economic, ecological, and social objectives (Figure 3).

In recent years, Vietnam's coffee industry has realized the importance of looking to the future to address its environmental and economic vulnerability. The Vietnamese government released the Vietnam Sustainable Coffee Plan Vision to 2030 [57] with targeted environmental directives, including exploring water-saving irrigation methods. Promoting regenerative agriculture practices such as the use of canopy trees and the shift to polyculture systems would not only shield coffee plants from the blistering sun of the Central Highlands but could also bring in extra money for growers, thereby serving as a buffer to world market coffee price fluctuations. The transition to diversified systems (Figure 3) better adapted to climate changes and more respectful of ecosystems and water resources (in keeping with SDGs 13 — 'climate action', 6 — 'clean water' and 15 — 'life and land') must be accelerated in Vietnam, while still striving to free families from poverty and achieve sustainable livelihoods (SDGs 1 — 'no poverty', and 8 — 'decent work and economic growth').

Example 3: traditional smallholder coffee polyculture transitions in Ethiopia

In Ethiopia, the primary center of origin and genetic diversity of *Coffea arabica* [58], coffee is seen as 'green gold' for the nation — it has long been the leading cash crop and export commodity [1]. Coffee is produced mostly by smallholders in Southwest Ethiopia (Figure 2) and is traditionally grown on farms ranging from small

(0.1 ha) homegardens (defined as carefully managed polycultures of useful plants on homesteads) to larger (0.93 ha) agroforestry systems [59] of varying complexity. As such, Ethiopian coffee is produced under a management gradient ranging from little-managed forests to intensive plantations [60,61]. Although these are stable agroecosystems that contribute to improved food security, regional and national economies, and environmental resilience, there are limitations on their potential productivity and economic return that must be overcome in order to achieve their full economic and ecological potential.

Agroforestry systems in Southwest Ethiopia are characterized by high plant species diversity. For example, in coffee-growing systems within the Yayu Biosphere Reserve, a total of 101 plant species from 49 families have been identified, with 74 being from homegardens (representing 37 botanical families) and 57 from coffee agroforestry systems (34 botanical families). About 38% of the plant composition in household gardens and 77% of the plant composition in coffee agroforestry systems consisted of indigenous species. Plant species diversity in homegardens was higher (Shannon's index H′ of 2.45) than in agroforestry systems (0.43) [59]. This agrobiodiversity contributes to rural food and nutrition security and reduces the impact of coffee price fluctuations on local economies by providing subsistence food products and alternative resources that can be sold, thereby effectively diversifying the agricultural commodity portfolios. [62]. For example, the *Enset*-coffee homegardens of the Sidama and Gedeo communities in southern Ethiopia include the perennial *Ensete ventricosum*, which serves as staple food for about 15 million people in the region [59].

However, Arabica coffee remains the major cash crop in the region and has been of great social and cultural value to smallholder farmers for centuries [58,63]. The relationship between yield and biodiversity in these systems is negative, and steep initial decline in species richness (especially among woody species that serve to provide shade cover) when yields increase up to around 750 kg/ha [42]. Optimal species composition, crop genetic diversity [64,65], and spatial organization must lead to the development of strategies to reduce the trade-off between increased yields and diversity. For instance, coffee genetic resources can be mobilized to better address farmers' needs. As the center of origin of wild *C. arabica*, Ethiopia hosts considerable genetic resources spanning wild, traditional, and improved material. The use of coffee varietal mixtures with different phenologies or that of more adequate genotypes, such as clones selected for high yield, drought tolerance, or better adapted to agroforestry systems [66], could also reduce production risks by increasing the resilience to environmental shocks and maximizing crop suitability in a given climate setting. This must be done in a way that respects the need for conserving wild *C. arabica* stands in their native environment.

In these systems, the use of chemical inputs is virtually absent, mainly because farmers cannot afford them, and system changes should continue to promote key ecosystem services that keep pest and disease pressure in coffee stands low [65]. The transition toward intensified coffee systems could generate higher yields and greater relative economic value from cultivated land (Figure 3) while still supporting sustainability and ecosystem services. Certification based on coffee origin is another potential avenue for increasing farmers' revenue [67]. Increasing yield and profitability of both coffee and associated cash crops is essential for preserving natural forests against agricultural expansion.

Overall, agroforestry systems in Ethiopia are agrobiodiversity rich, provide multiple benefits, and, provided that they are not associated with increased deforestation, can offer a sustainable land use system aligned with SDGs 13 ('climate action') and 15 ('life and land'). However, efforts are needed to further the economic aspects of sustainability and improve resilience in order to maximize the contribution to smallholder farmers' livelihoods (aligned with SDGs 1 — 'no poverty' and 8 — 'decent work and economic growth').

Conclusion and outlook

From a socioeconomic perspective, understanding the extent of climate-driven impacts on coffee production and the benefits of potential adaptation strategies will be of vital importance to maintaining and improving coffee productivity and profitability and sustaining the livelihoods of smallholder producers worldwide [68]. In light of the high diversity of coffee farming systems, it would be inappropriate to propose simple, generalized solutions for technical progress. Instead, participative approaches with local actors [69] are needed to consider context-specific information. This should include building on the perceptions and experience of local farmers [70] and their past responses to climate change and shocks. The frequent divergence between socioeconomic and ecological research approaches should be avoided [71] and instead integrated, especially through interdisciplinary socioecological research. More socioeconomic studies are also needed [72]. The economic valuation of ecological and social services delivered by coffee at plot, farm, and landscape levels is still in its infancy.

Agroforestry can increase farmers' adaptive capacity and help them cope with risk and uncertainty. Yet considerable research gaps remain, especially due to the uneven geographic distribution of studies, uneven knowledge on specific climate hazards, and the lack of integrated biophysical–socioeconomic research [73]. This is especially relevant for coffee, where most studies focus on the Americas [74]. Notably, few papers have focused on coffee cropping systems at regional, national, or local scales in Vietnam [27,53], despite its position as the world's second largest coffee-producing country [15]. Current research in the Americas predominantly concerns Arabica, with limited consideration of Robusta, particularly at national and sub-national scales, while being mainly focused on the influence of climate change on coffee suitability [6,75] rather than coffee yield. Although only discussed here for coffee, the discussed interactions between agricultural diversification and sustainability (both economic and ecological) may also be applicable to other tropical commodities generated by agroforestry systems, such as cacao.

To summarize, the social, economic, and ecological dimensions of sustainability and resilience must be integrated into coffee farming systems, and this could be achieved through diversification processes. However, due to the fact that coffee production scenarios differ markedly, it is impossible to identify a universal, 'one-size-fits-all' approach. Instead, different pathways need to be designed for different contexts.

Funding
This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement
Conceptualization: **VP**, **CA**; Data curation and figure design: **CA**; Methodology: **VP**, **CA**, and **PvA**; Writing – original draft: **VP**, **CA**; Writing – review & editing: **VP**, **CA, PV, PM** and **PV**.

Data Availability

We have used published data.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References and recommended reading
Papers of particular interest, published within the period of review, have been highlighted as:

- • of special interest
- •• of outstanding interest

1. Outlook I.C.O International Coffee Organisation, 2023. https://icocoffee.org/documents/cy2022-23/Coffee_Report_and_Outlook_April_2023_-_ICO.pdf.

2. United Nations. Transforming Our World: The 2030 Agenda for Sustainable Development. 2015; Department of Economic and Social Affairs. https://sdgs.un.org/2030agenda.

3. Enveritas: 2019. https://carto.com/blog/enveritas-coffee-poverty-visualization.

4. Harvey CA, Pritts AA, Zwetsloot MJ, Jansen K, Pulleman MM, Armbrecht I, Avelino J, Barrera JF, Bunn C, García JH, *et al.*: **Transformation of coffee-growing landscapes across Latin America. A review**. *Agron Sustain Dev* 2021, **41**:62.

5. Convention on Biological Diversity (CBD): Nations Adopt Four Goals, 23 Targets for 2030 in Landmark UN Biodiversity Agreement; 2022, https://www.cbd.int/article/cop15-cbd-press-release-final-19dec2022.

6. •• Tournebize R, Borner L, Manel S, Meynard CN, Vigouroux Y, Crouzillat D, Fournier C, Kassam M, Descombes P, Tranchant-Dubreuil C, *et al.*: **Ecological and genomic vulnerability to climate change across native populations of Robusta coffee (*Coffea canephora*)**. *Glob Change Biol* 2022, **28**:4124-4142.
The authors studied the genomic and ecological vulnerability and their interaction in *Coffea canephora* across its native range in Africa in a 2050 time horizon for a variety of climate change scenarios. Genomic vulnerability was estimated to be 23% higher in populations where habitat will be lost in 2050 compared to regions where habitat will remain suitable. This highlights the importance of considering local adaptation to understand species' responses to climate change.

7. Sharma R, Mina U, Kumar BM: **Homegarden agroforestry systems in achievement of Sustainable Development Goals. A review**. *Agron Sustain Dev* 2022, **42**:44.

8. • Beillouin D, Ben-Ari T, Malézieux E, Seufert V, Makowski D: **Positive but variable effects of crop diversification on biodiversity and ecosystem services**. *Glob Change Biol* 2021, **27**:4697-4710.
This meta-analysis, while not specifically focused on coffee, explores and compares the impacts of several diversification strategies that generally have a positive effect. However, the authors note that some strategies are potentially better than others. As the push toward greater sustainability is necessarily context specific, knowledge on the relative usefulness of different strategies is essential for decision-making.

9. Ferguson P, Wollersheim L: **From sustainable development to resilience? (Dis)continuities in climate and development policy governance discourse**. *Sustain Dev* 2023, **31**:67-77.

10. Egli L, Mehrabi Z, Seppelt R: **More farms, less specialized landscapes, and higher crop diversity stabilize food supplies**. *Environ Res Lett* 2021, **16**:055015.

11. Siles P, Cerdán CR, Staver C: **Smallholder coffee in the global economy — a framework to explore transformation alternatives of traditional agroforestry for greater economic, ecological, and livelihood viability**. *Front Sustain Food Syst* 2022, **6**:808207. https://doi.org/10.3389/fsufs.2022.808207.

12. International Trade Centre, The Coffee Guide, Fourth ed., 2021, ITC. https://intracen.org/resources/publications/the-coffee-guide-fourth-edition.

13. Oakley JL, Bicknell JE: **The impacts of tropical agriculture on biodiversity: a meta-analysis**. *J Appl Ecol* 2022, **59**:3072-3082.

14. Yang T, Siddique KHM, Liu K: **Cropping systems in agriculture and their impact on soil health — a review**. *Glob Ecol Conserv* 2020, **23**:e01118.

15. ICO International Coffee Organization Statistics, 2019. International Coffee Organisation. http://www.ico.org/trade_statistics.asp.

16. Anderzén J, Méndez VE, Griffeth M, McHugh C, Gilman C, Barahona C, Peyser R: State of the Smallholder Coffee Farmer: An Initiative Towards a More Equitable and Democratic Information Landscape, 2021, Research Report. https://coffeesmallholder.org/docs/State%20of%20the%20Smallholder%20Coffee%20Farmer.pdf.

17. Dow Goldman E, Weisse M, Harris N, Schneider M: **Estimating the role of seven commodities in agriculture-linked deforestation: oil palm, soy, cattle, wood fiber, cocoa, coffee, and rubber**. *World Resour Inst* 2020, https://doi.org/10.46830/writn.na.00001

18. Habel JC, Rasche L, Schneider UA, Engler JO, Schmid E, Rödder D, Meyer ST, Trapp N, Sos del Diego R, Eggermont H, *et al.*: **Final countdown for biodiversity hotspots**. *Conserv Lett* 2019, **12**:e12668.

19. Kissinger G: **Policy responses to direct and underlying drivers of deforestation: examining rubber and coffee in the Central Highlands of Vietnam**. *Forests* 2020, **11**:733.

20. Regulation (EU) 2023/1115 of the European Parliament and of the Council of 31 May 2023 on the Making Available on the Union Market and the Export From the Union of Certain Commodities and Products Associated With Deforestation and Forest Degradation and Repealing Regulation (EU) No 995/2010; 2023, https://eur-lex.europa.eu/eli/reg/2023/1115/oj.

21. ICO: EU Action Against Deforestation and Forest Degradation — EUDR**:** the ICO Task Force Becomes a Strategic Partner in Building Consensus on a Deforestation-free Coffee Supply Chain; 2023, https://icocoffee.org/documents/cy2022-23/pr-341e-cpptf-webinar-deforestation.pdf?mc_cid=c7511be6e4&mc_eid=c9377207e6.

22. In *Commodity Markets: Evolution, Challenges, and Policies*. Edited by Baffes J, Nagle P. The World Bank; 2022.

23. Guido Z, Knudson C, Rhiney K: **Will COVID-19 be one shock too many for smallholder coffee livelihoods?** *World Dev* 2020, **136**:105172.

24. Jawo TO, Kyereh D, Lojka B: **The impact of climate change on coffee production of small farmers and their adaptation strategies: a review**. *Clim Dev* 2022, **0**:1-17.

25. Pham Y, Reardon-Smith K, Mushtaq S, Cockfield G: **The impact of climate change and variability on coffee production: a systematic review**. *Clim Change* 2019, **156**:609-630.

26. Bunn C, Läderach P, Ovalle Rivera O, Kirschke D: **A bitter cup: climate change profile of global production of Arabica and Robusta coffee**. *Clim Change* 2015, **129**:89-101.

27. •• Dinh TLA, Aires F, Rahn E: **Statistical analysis of the weather impact on Robusta coffee yield in Vietnam**. *Front Environ Sci* 2022, **10**:820916, https://doi.org/10.3389/fenvs.2022.820916.

This study presents a 'success story' of regenerative coffee farming practices in smallholder coffee plantations in Vietnam. Their effects were evaluated ecologically and economically at the farm scale by comparison with conventional systems. Regenerative farming practices promote biodiversity and decrease external inputs through a system of crop diversification that improves productivity and economic performance while preserving the ecological and environmental integrity of the landscape.

28. Kath J, Craparo A, Fong Y, Byrareddy V, Davis AP, King R, Nguyen-Huy T, van Asten PJA, Marcussen T, Mushtaq S, *et al.*: **Vapour pressure deficit determines critical thresholds for global coffee production under climate change**. *Nat Food* 2022, **3**, https://doi.org/10.1038/s43016-022-00614-8

29. Jaramillo J, Muchugu E, Vega FE, Davis A, Borgemeister C, Chabi-Olaye A: **Some like it hot: the influence and implications of climate change on coffee berry borer (*Hypothenemus hampei*) and coffee production in East Africa**. *PLoS One* 2011, **6**:e24528.

30. Zewdie B, Tack AJM, Ayalew B, Adugna G, Nemomissa S, Hylander K: **Temporal dynamics and biocontrol potential of a hyperparasite on coffee leaf rust across a landscape in Arabica coffee's native range**. *Agric Ecosyst Environ* 2021, **311**:107297.

31. Kutywayo D, Chemura A, Kusena W, Chidoko P, Mahoya C: **The impact of climate change on the potential distribution of agricultural pests: the case of the coffee white stem borer (*Monochamus leuconotus* P.) in Zimbabwe**. *PLoS One* 2013, **8**:e73432.

32. Kath J, Byrareddy VM, Reardon-Smith K, Mushtaq S: **Early flowering changes robusta coffee yield responses to climate stress and management**. *Sci Total Environ* 2023, **856**:158836.

33. Gomez C, Despinoy M, Hamon S, Hamon P, Salmon D, Akaffou DS, Legnate H, de Kochko A, Mangeas M, Poncet V: **Shift in precipitation regime promotes interspecific hybridization of introduced *Coffea* species**. *Ecol Evol* 2016, **6**:3240-3255.

34. Tavares P da S, Giarolla A, Chou SC, Silva AJ de P, Lyra A de A: **Climate change impact on the potential yield of Arabica coffee in southeast Brazil**. *Reg Environ Change* 2018, **18**:873-883.

35. Imbach P, Fung E, Hannah L, Navarro-Racines CE, Roubik DW, Ricketts TH, Harvey CA, Donatti CI, Läderach P, Locatelli B, *et al.*: **Coupling of pollination services and coffee suitability under climate change**. *Proc Natl Acad Sci* 2017, **114**:10438-10442.

36. DaMatta FM, Godoy AG, Menezes-Silva PE, Martins SCV, Sanglard LMVP, Morais LE, Torre-Neto A, Ghini R: **Sustained enhancement of photosynthesis in coffee trees grown under free-air CO_2 enrichment conditions: disentangling the contributions of stomatal, mesophyll, and biochemical limitations**. *J Exp Bot* 2016, **67**:341-352.

37. Verburg R, Rahn E, Verweij P, van Kuijk M, Ghazoul J: **An innovative perspective to climate change adaptation in coffee systems**. *Environ Sci Policy* 2019, **97**:16-24.

38. •• Schmidt PG, Bunn C: **Coordinated implementation of climate-smart practices in coffee farming increases benefits at farm, landscape and global scale**. *Front Clim* 2021, **3**:746139, https://doi.org/10.3389/fclim.2021.746139.

This literature review explores how local adoption of climate-smart practices might be applicable to coffee farming systems and identifies benefits at local, landscape and global scales. They group the impacts into seven functional groups: soil characteristics, water management, crop and genetic diversity, climate buffer and adjustment, crop nutrient management, structural elements and natural habitats, and system functioning. The authors discuss considerations for managing potential conflicts of interest and call for co-ordination between local farmers, policy makers, and global donors.

39. Renard D, Tilman D: **National food production stabilized by crop diversity**. *Nature* 2019, **571**:257-260.

40. •• Teixeira HM, Schulte RPO, Anten NPR, Bosco LC, Baartman JEM, Moinet GYK, Reidsma P: **How to quantify the impacts of diversification on sustainability? A review of indicators in coffee systems**. *Agron Sustain Dev* 2022, **42**:62.

This systematic literature review focused on agroforestry coffee systems to assess the impact of diversification on multiple sustainability dimensions. The indicators identified could be classified in one of the sustainability dimensions proposed: ecosystem services (57.2%), biodiversity (35.6%), input use (4%), socioeconomic sustainability (2.7%), and resilience capacity (0.5%). The impact of diversification was more positive than negative with regard to all sustainability dimensions, with the exception of crop productivity.

41. • Zhang X, Yao G, Vishwakarma S, Dalin C, Komarek AM, Kanter DR, Davis KF, Pfeifer K, Zhao J, Zou T, *et al.*: **Quantitative assessment of agricultural sustainability reveals divergent priorities among nations**. *One Earth* 2021, **4**:1262-1277.

This study offers a Sustainable Agriculture Matrix to quantify the performance of countries worldwide based on historical data on environmental, social, and economic indicators of agriculture. The results reveal priority areas for improvement per country and show that the trade-offs and synergies among indicators often differ.

42. Zewdie B, Tack AJM, Ayalew B, Wondafrash M, Nemomissa S, Hylander K: **Plant biodiversity declines with increasing coffee yield in Ethiopia's coffee agroforests**. *J Appl Ecol* 2022, **59**:1198-1208.

43. Cordes, Kaitlin and Sagan, Margaret and Kennedy, Solina, Responsible Coffee Sourcing: Towards a Living Income for Producers (July 1, 2021). Available at SSRN: doi: 10.2139/ssrn.3894124.

44. •• Gomes LC, Bianchi FJJA, Cardoso IM, Fernandes RBA, Filho EIF, Schulte RPO: **Agroforestry systems can mitigate the impacts of climate change on coffee production: a spatially explicit assessment in Brazil**. *Agric Ecosyst Environ* 2020, **294**:106858.

This paper predicts climate-change induced shifts in suitable land for coffee cultivation in Brazil, that is, the world's leading producer. The results also support agroforestry as a viable mitigation strategy, as its ability to buffer temperature changes can help farm systems remain suitable for coffee. There are particularly high stakes for coffee cultivation in Brazil, so these results are of particular interest as they strengthen arguments advocating greater sustainability.

45. Moreira SLS, Pires CV, Marcatti GE, Santos RHS, Imbuzeiro HMA, Fernandes RBA: **Intercropping of coffee with the palm tree, macauba, can mitigate climate change effects**. *Agric Meteor* 2018, **256–257**:379-390.

46. Zaro GC, Caramori PH, Yada Junior GM, Sanquetta CR, Filho AA, Nunes ALP, Prete CEC, Voroney P: **Carbon sequestration in an**

agroforestry system of coffee with rubber trees compared to open-grown coffee in southern Brazil. *Agrofor Syst* 2020, **94**:799-809.

47. Perdoná MJ, Soratto RP: **Arabica coffee–macadamia intercropping: a suitable macadamia cultivar to allow mechanization practices and maximize profitability**. *Agron J* 2016, **108**:2301-2312.

48. Campanha MM, Santos RHS, de Freitas GB, Martinez HEP, Garcia SLR, Finger FL: **Growth and yield of coffee plants in agroforestry and monoculture systems in Minas Gerais, Brazil**. *Agrofor Syst* 2004, **63**:75-82.

49. Rezende MQ, Venzon M, dos Santos PS, Cardoso IM, Janssen A: **Extrafloral nectary-bearing leguminous trees enhance pest control and increase fruit weight in associated coffee plants**. *Agric Ecosyst Environ* 2021, **319**:107538.

50. Venzon M: **Agro-ecological management of coffee pests in Brazil**. *Front Sustain Food Syst* 2021, **5**:721117.

51. Phan VH: **Research results on Robusta coffee breeding in Vietnam**. *Vietnam J Sci Technol Eng* 2017, **59**:37-41.

52. Bunn C, Läderach P, Ovalle Rivera O, Kirschke D: **A bitter cup: climate change profile of global production of Arabica and Robusta coffee**. *Clim Change* 2015, **129**:89-101.

53. •• Le QV, Cowal S, Jovanovic G, Le D-T: **A study of regenerative farming practices and sustainable coffee of ethnic minorities farmers in the Central Highlands of Vietnam**. *Front Sustain Food Syst* 2021, **5**:712733.

This study presents a ‘success story’ of regenerative coffee farming practices in smallholder coffee plantations in Vietnam. Their effects were evaluated ecologically and economically at the farm scale by comparison with conventional systems. Regenerative farming practices promote biodiversity and decrease external inputs through a system of crop diversification that improves productivity and economic performance while preserving the ecological and environmental integrity of the landscape.

54. Elevitch C, Mazaroli D, Ragone D: **Agroforestry standards for regenerative agriculture**. *Sustainability* 2018, **10**:3337.

55. Cerda R, Avelino J, Harvey CA, Gary C, Tixier P, Allinne C: **Coffee agroforestry systems capable of reducing disease-induced yield and economic losses while providing multiple ecosystem services**. *Crop Prot* 2020, **134**:105149.

56. Allinne C, Savary S, Avelino J: **Delicate balance between pest and disease injuries, yield performance, and other ecosystem services in the complex coffee-based systems of Costa Rica**. *Agric Ecosyst Environ* 2016, **222**:1-12.

57. FFTC Agricultural Policy Platform (FFTC-AP), Vietnam Sustainable Coffee Plan Till 2020 and Vision to 2030, 2016. https://ap.fftc.org.tw/article/1118.

58. Labouisse JP, Bellachew B, Kotecha S, Bertrand B: **Current status of coffee (*Coffea arabica* L.) genetic resources in Ethiopia: implications for conservation**. *Genet Resour Crop Evol* 2008, **55**:1079-1093.

59. Seid G, Kebebew Z: **Homegarden and coffee agroforestry systems plant species diversity and composition in Yayu Biosphere Reserve, southwest Ethiopia**. *Heliyon* 2022, **8**:e09281.

60. Zewdie B, Tack AJM, Adugna G, Nemomissa S, Hylander K: **Patterns and drivers of fungal disease communities on Arabica coffee along a management gradient**. *Basic Appl Ecol* 2020, **47**:95-106.

61. Shimales T, Mendesil E, Zewdie B, Ayalew B, Hylander K, Tack AJM: **Management intensity affects insect pests and natural pest control on Arabica coffee in its native range**. *J Appl Ecol* 2023, **60**:911-922.

62. Jemal OM, Callo-Concha D, van Noordwijk M: **Coffee agroforestry and the food and nutrition security of small farmers of South-Western Ethiopia**. *Front Sustain Food Syst* 2021, **5**:608868.

63. Dinegde HG, Bekele AE, Sima AD: **The impact of cash saving on the food security status of smallholder coffee farmers: evidence from southwest Ethiopia**. *Int J Soc Econ* 2022, **49**:1497-1517.

64. Millet CP, Allinne C, Vi T, Marraccini P, Verleysen L, Couderc M, Ruttink T, Zhang D, Solano-Sanchez W, Tranchant-Dubreuil C, Jeune W, Poncet V: **Haitian coffee agroforestry systems harbor complex Arabica variety mixtures and under-recognized genetic diversity**. *PLoS One* 2024, https://doi.org/10.1371/journal.pone.0299493

65. •• Zewdie B, Bawin Y, Tack AJM, Nemomissa S, Tesfaye K, Janssens SB, Van Glabeke S, Roldán-Ruiz I, Ruttink T, Honnay O, *et al.*: **Genetic composition and diversity of Arabica coffee in the crop’s centre of origin and its impact on four major fungal diseases**. *Mol Ecol* 2022, **00**:1-20.

This is a rare example of a study that integrates genetic, social science, and phytopathology along a management intensity gradient, ranging from nearly wild to intensively managed coffee stands in Ethiopia. They observed that genetic diversity was higher in less managed sites and explored how this variation was related to the incidence of four major fungal diseases.

66. Breitler J-C, Etienne H, Léran S, Marie L, Bertrand B: **Description of an Arabica coffee ideotype for agroforestry cropping systems: a guideline for breeding more resilient new varieties**. *Plants* 2022, **11**:2133.

67. Mitiku F, Nyssen J, Maertens M: **Certification of semi-forest coffee as a land-sharing strategy in Ethiopia**. *Ecol Econ* 2018, **145**:194-204.

68. Nature Editorial: **Ending hunger: science must stop neglecting smallholder farmers**. *Nature* 2020, **586**:336.

69. Andreotti F, Speelman EN, Van den Meersche K, Allinne C: **Combining participatory games and backcasting to support collective scenario evaluation: an action research approach for sustainable agroforestry landscape management**. *Sustain Sci* 2020, **15**:1383-1399.

70. Archibald S, Allinne C, Cerdán CR, Isaac ME: **From the ground up: patterns and perceptions of herbaceous diversity in organic coffee agroecosystems**. *Ecol Solut Evid* 2022, **3**:e12166.

71. Hirons M, Mehrabi Z, Gonfa TA, Morel A, Gole TW, McDermott C, Boyd E, Robinson E, Sheleme D, Malhi Y, *et al.*: **Pursuing climate resilient coffee in Ethiopia — a critical review**. *Geoforum* 2018, **91**:108-116.

72. Jezeer RE, Verweij PA, Santos MJ, Boot RGA: **Shaded coffee and cocoa — double dividend for biodiversity and small-scale Farmers**. *Ecol Econ* 2017, **140**:136-145.

73. Quandt A, Neufeldt H, Gorman K: **Climate change adaptation through agroforestry: opportunities and gaps**. *Curr Opin Environ Sustain* 2023, **60**:101244.

74. Vignola R, Esquivel MJ, Harvey C, Rapidel B, Bautista-Solis P, Alpizar F, Donatti C, Avelino J: **Ecosystem-based practices for smallholders’ adaptation to climate extremes: evidence of benefits and knowledge gaps in Latin America**. *Agronomy* 2022, **12**:2535.

75. de Aquino SO, Kiwuka C, Tournebize R, Gain C, Marraccini P, Mariac C, Bethune K, Couderc M, Cubry P, Andrade AC, *et al.*: **Adaptive potential of *Coffea canephora* from Uganda in response to climate change**. *Mol Ecol* 2022, **31**:1800-1819.