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Agronomic practices toward coffee sustainability. A review

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ABSTRACT: The coffee sector is estimated to have a retail market value in excess of USD 83 billion, and over 125 million jobs have been created in the global coffee chain. The coffee specialty market has recently increased significantly, generating opportunities to certify coffee beans produced by sustainable practices. This avoids practices potentially harmful to the environment. Agroforestry, organic farming, intercropping, and soil conservation strategies are examples of sustainable alternatives in the production of coffee. In this review, we focus on practices for the sustainable management of coffee plantations that can help farmers fight problems caused by global warming. More specifically, we address soil organic matter and microbiota, the use of *Urochloa* grass as intercrop in coffee plantations, shading systems (including agroforestry), and organic coffee production. We concluded that from the agronomic viewpoint, we already have production techniques that can replace traditional ones with significant advantages accruing to the quality of coffee orchard ecosystems. Nevertheless, we need scientific research efforts to deal with the existing gaps and the engagement of the whole coffee chain as a means of guaranteeing an adequate profit to those smallholders who adopt and maintain sustainable practice and are capable of bringing several positive changes to the coffee crop, including the use of microbia-based commercial products and new organic sources of nutrients to complement chemical fertilizers and improve coffee quality.

Keywords: *Coffea arabica* L., global warming, climate changes, management systems

Introduction

Perhaps the simplest way to precisely define the word sustainability was suggested by the World Commission on Environment and Development (WCED) in the document "Our Common Future", released in 1987: "Sustainability is the development that meets the needs of the present generation without compromising the ability of future generations to meet their needs" (Holdgate, 1987). At the 2005 World Summit - WCED, it became clear that sustainability, as defined above, must integrate environmental, social, and economic demands (Holdren, 2008). Transposing this concept to agriculture, sustainable agriculture can be seen as the production of food to meet the needs of the present generation without compromising future food production, requiring the interaction of environmental, social, and economic demands to govern the entire food chain from the field to the supermarket shelves.

Most crops grow in places that, to some extent, do not favor plant growth. Mankind has succeeded in producing food crops by developing technologies that improve the plant performance of, for example, irrigation and fertilizers (Pretty, 2008). Meteorological advances have also helped agriculture scientists study the impact of weather and climate on crops and oriented farmers about several measures, from sowing to harvest (Parolini, 2022). Technologies available now and the many to come are essential for keeping food production in line with a global population that is estimated to grow from 7.7 billion to 9.7 billion people by 2050 and nearly 11 billion circa 2100 (United Nations, 2022).

Sustainability is a timely subject, and it will become even more important in agriculture, considering the climate changes caused by the increase in greenhouse gases in the atmosphere. A rise in the global temperature may have a sizeable effect on agriculture because of its direct impact on plant metabolism (Drake et al., 1997; Dusenge et al., 2019) and changes in the water regimes that can ultimately lead to droughts and irregular rain distribution (Arnell, 1999; Oki and Kanae, 2006; Rosa et al., 2020). Additionally, global warming will affect the soil primarily in the following two ways: organic matter may be oxidized faster, and soil microbiota may change (Trumbore, 1997; Conant et al., 2011; Baveye et al., 2020). Intensive agriculture may also increase the degradation of organic matter in the soil due to the high degree of mechanization (Purwanto and Alam, 2020) in crops such as maize (*Zea mays* L.) and soybean (*Glycine max* L. Merr). Changes in soil organic matter and water regime can drastically affect plant nutrient use efficiency and thereby impact the effectiveness of fertilizers.

According to reports from the International Coffee Organization (see: https://ico.org/), Brazil leads coffee production globally, followed by Vietnam and Colombia. While Vietnan produces mostly the *Coffea canephora* species (Robusta coffee), *Coffea arabica* predominates in Brazil and Colombia. Because of frosts over the last 50 years, coffee cultivation in Brazil has migrated from the southern states (São Paulo and

Paraná) to the warmer regions of the Brazilian central-western states (such as Bahia and the north of Minas Gerais) thanks to irrigation (Zullo et al., 2011; Vicente et al., 2017). Thus, global warming may make these new areas even more dependent on irrigation, which will call for extra water management efforts. The impact of increasing temperatures on coffee cultivation was also evaluated by Zullo et al., (2006), who estimated that increasing the temperature by 1 °C, 3 °C, and 5.8 °C may decrease the low-risk climatic areas for coffee plantations from 78.7 % (current situation) of the total area of the state of São Paulo to 58.9 %, 30.3 %, and 3.3 %, respectively. In contrast, a rise in temperature of between 1 °C and 4 °C would force coffee again to the south of the country, reaching the border of Uruguay and Argentina, which are nowadays inappropriate areas on account of the frequent occurrence of frosts (Zullo et al., 2011).

On the other hand, in 2017, the global coffee sector's value was estimated at USD 83 billion and provided 125 million jobs (Voora et al., 2019). Of the 12.5 million coffee farms worldwide, 67 to 80 % are smallholder farms, many smaller than 5 ha, and located in third-world countries (Voora et al., 2019).

In this scenario, the production of coffee under a sustainable system can support small farmers entering the specialty coffee market, which reduces coffee production costs, diversifies income, and addresses livelihood needs.

In particular, the market for certified organic coffee is advantageous due to its fast-growing demand, but only 3 % of world coffee production meets the requirements for this certification. The impact of certification programs on coffee smallholder livelihood assets overlay with complex social, economic, cultural, and political aspects, with positive impacts exceeding negative impacts (Bray and Neilson, 2017).

We are aware that coffee chain sustainability encompasses many aspects that are beyond this paper's scope. The risks associated with the entire chain are environmental, social and economic in nature. Given this, we refer to the review article of Peixoto et al. (2023). These authors present a detailed discussion of the sustainability problems of the coffee chain as a whole and the challenges related to the issue in coffee production, processing, and consumption. Among these is the role of sustainable certifications, corporate sustainability initiatives, direct trade, origin denomination, waste management, and byproduct valorization.

In addition, considering the coffee chain's extension and complexity, the dominant companies in this sector are, or should need to be, important partners in achieving sustainability. Their role and corporate sustainability initiatives, challenges, and efforts were depicted by Bager and Lambin (2020). Unfortunately, these authors concluded that sustainability issues such as climate change and deforestation remain under-addressed by most coffee companies.

In this review, we cover sustainable practices for coffee cultivation considered important in the case where global warming predictions are confirmed. First, we focus on organic matter and soil microbiota and discuss the role of microorganisms in coffee production. Second, we examine the advantages of intercropping coffee with *Urochloa* grass as regards soil characteristics, nutrient cycling, and water use. Third, we discuss the use of shading in coffee production and its consequences on the crop microclimate and bean quality. Finally, we review the production of organic coffee considering the market niches and the use of organic manures as fertilizers. The sustainable practices mentioned in this review are integrated into Figure 1 as a guide for the reader.

Literature search methodology

For the literature survey, we systematically searched electronic databases: ISI, Web of Science, AGRIS, Scielo, and Google Scholar, for published papers, mainly from 2000 to 2023, although several prior classical studies were also considered where appropriate. The Digital Library of Theses and Dissertations of the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) was used to search for studies that may not have been published in scientific journals. We performed independent literature searches for each of the following terms: "coffee*" AND "organic management" AND "shading", "agroforestry"; "agroforestry coffee systems", "sustainability", "intercropping", where an asterisk represented truncation. We also conducted searches using specific keywords on agroforestry and intercropping practices in combination with variables associated with soil quality, organic matter, water management, nutrient cycling, soil microbial activity, and plant growth promotion rhizobacteria, biofertilizers, among others. Articles and theses were identified for potential inclusion by assessing three components of the study: title, abstract and full text. In addition, we searched manually for papers cited in previous reviews, meta-analyses, and book chapters which considered related topics within the focus of interest of this review (Andrade et al., 2009; Baptistella et al., 2020; Barrios et al., 2012; Matta, 2004; Duong et al., 2020, 2021; Hameed et al., 2020; Martinez et al., 2019). A narrative review was elaborated, synthesizing the main results found in relevant articles and theses.

Coffee management: soil quality and ecosystem services

Soil quality is defined as "the capacity of a soil to function within ecosystem and land-use boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health" (Doran and Jones, 1997). Furthermore, the concept of ecosystem services is related to the various functions and processes of natural and modified ecosystems that support human existence and whose economic value can be estimated (Sandhu et

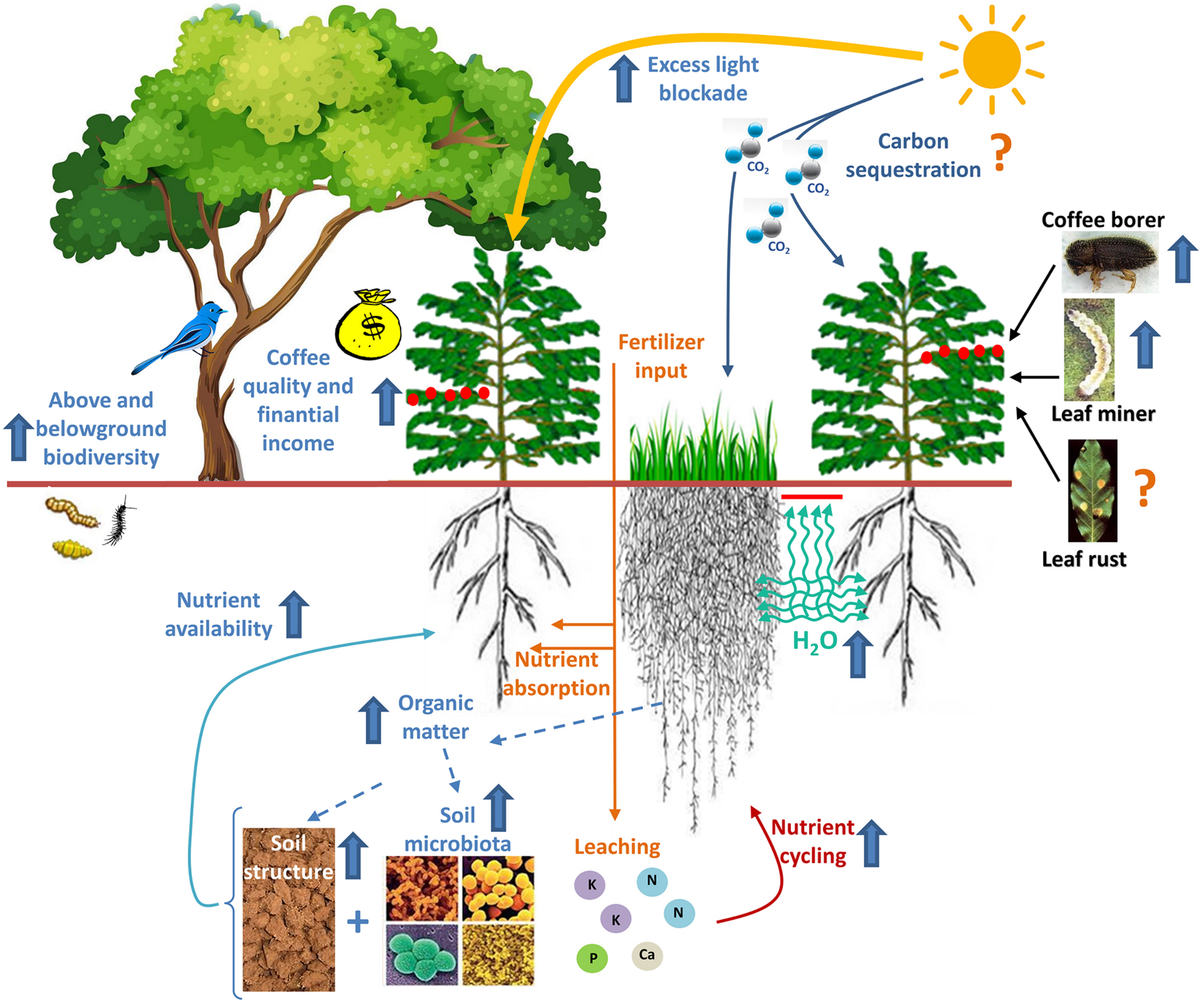

Figure 1 – Sustainable practices in coffee plantations. Blue arrows indicate benefits for the crop system. An increase in organic matter in the soil improves microbiota, nutrient cycling and availability, soil water retention, and physicochemical and biological soil characteristics. Intercropping with grasses and legumes may provide favorable conditions for pest natural enemies, and in addition to shading trees and the coffee plant, may enable an increase in carbon sequestration. Shading provided by intercropped trees avoids high light and extreme temperature stresses. It also improves coffee quality and price, which, together with timber exploration, may bring social and financial benefits to smallholder farmers. Sustainable practices favor above and belowground biodiversity.

al., 2010; De Leijster et al., 2021). Ecosystem services in agriculture include providing goods and services, supporting and regulating services, and cultural services (Sandhu et al., 2010).

Conventional practices in intensive agriculture may be environmentally harmful, leading to soil contamination, nutrient imbalances, salinity, soil erosion, disruption of soil biota-related processes, and losses in soil biodiversity, with an overall reduction in soil quality and degradation of several ecosystem services (Nellemann et al., 2009). Organic agriculture searches for the sustainability of the production systems by using and preserving ecosystem services (Sandhu et al., 2010). In this respect, in addition to organic coffee practices strongly appealing to environmentally concerned consumers, scientific evidence of organic systems improving soil health and quality is being collected (Blackman and Naranjo, 2012).

In coffee plantations, organic and agroforestry systems have been linked to the concept of soil quality to reduce the environmental damage of intensive agriculture, maintaining higher biodiversity and ecosystem services such as nutrient cycling and control of pathogen and pest control (Jezeer et al., 2019; Duong et al., 2020; De Leijster et al., 2021; Gagliardi et al., 2022). Coffee production systems, also challenged by global climate change, need to adopt management practices to mitigate the negative effects of more frequent drought periods, shorter wet seasons, and extreme weather events, and thus avoid soil erosion and losses in soil fertility and productivity (Wagner et al., 2021; Cassamo et al., 2023). Generally, organic-based management in coffee plantations has been related to trends of reducing greenhouse gas emissions when compared to intensive coffee management. However, the extent of these reductions depends on factors such as soil type, age of the system, shade tree species, and inorganic or organic nitrogen (N) fertilizer inputs (Noponen et al., 2012; Chatterjee et al., 2019; Bentzon-Tarp et al., 2023).

Practices that preserve soil organic matter improve soil quality as organic carbon compounds enhance cation exchange capacity and soil microbial activity and reduce exchangeable aluminum and phosphate adsorption to soil colloids (Doran and Parkin, 2015). This is especially relevant in tropical and subtropical regions where most coffee is cultivated. In these regions, soils are prone to intense weathering processes and conventional coffee management, including tillage and no soil cover, which may exacerbate soil organic matter decline. Furthermore, organic, intercrop, and shaded coffee practices generally increase and maintain soil organic matter contents (Pimentel et al., 2011). For instance, shade trees in agroforestry coffee plantations increase litter content on topsoil, build up soil organic matter and increase nutrient availability. In turn, higher soil organic matter contents allow for a richer soil biota key for nutrient cycling (Barrios et al., 2012), an ecosystem service that reduces the need for chemical fertilizer inputs. A study conducted in the province of Yunnan, China, showed that four years after converting an intensively managed open coffee plantation into an intensive agroforestry system was sufficient to observe the positive impact of shade trees on soil quality (Rigal et al., 2020). This was especially evident during the dry season, with higher soil organic matter contents, total N, and available phosphorus (P) and calcium (Ca) than in the open coffee plantation (Rigal et al., 2020), as deep-rooted trees improve water infiltration, and avoid soil erosion as well as nutrient cycling (Tully et al., 2012). As regards this last benefit, by using tension lysimeters and a model for water balance, nutrient leaching losses were estimated in coffee agroforest soils amended with mineral and organic fertilizers. Although nutrient losses did not differ between amendments, N losses declined as the shade tree biomass increased (Tully et al., 2012), highlighting a crucial ecosystem service provided by trees in mitigating nutrient losses (De Leijster et al., 2021). In addition, tree shade in agroforestry systems improves soil moisture retention, which has been shown to buffer drought effects, and improve coffee productivity (Wagner et al., 2021). However, caution should be exercised as coffee agroforestry systems do not always improve soil organic C stocks, especially in deeper soil profiles (Chatterjee et al., 2019).

Soil microbiota and their activities are good indicators of soil quality and main players in soil organic matter decomposition, nutrient cycling, and pathogen control (Doran and Parkin, 2015), and have been used to compare the impacts of coffee management systems (Munroe et al., 2015; Duong et al., 2020; Fulthorpe et al., 2020). Soil biological diversity is usually higher in coffee orchards under organic and agroforestry management systems than under intensive management (Santos et al., 2018; Rao et al., 2020). However, contrasting results are also found where higher microbial richness and diversity were observed in the rhizosphere of pesticide-treated coffee farms than in those following organic practices (Caldwell et al., 2015). The authors suggested that soil chemical characteristics and plant density in the organic farms studied were perhaps not optimal for coffee growth, leading to these unexpected results (Caldwell et al., 2015). Soil nitrifier populations, a functional group related to inorganic N dynamics, showed marked differences in coffee under N_2-fixing shade tree and monoculture systems. The latter system also showed greater N accumulation in the rhizosphere of coffee, suggesting significant N incorporation into the soil by N_2-fixation activity (Munroe et al., 2015).

Sustainable pathogen management in biodiverse and organically managed agroecosystems is central to actual climate changes. In a recent study based on a gradient of coffee leaf rust incidence in *C. arabica* var. Caturra farms in Costa Rica, the complex and significant effects of amendments shaping coffee's belowground resource acquisition strategies and multi-species collaborations were verified, where under organic amendments expressed greater acquisitive traits and enhanced collaboration with symbiotic fungi and saprotrophs (Gagliardi et al., 2022).

A key group of soil microorganisms whose diversity and composition have been assessed when measuring soil quality in agroecosystems is arbuscular mycorrhizal fungi (AMF). Their effects in promoting plant health and nutrient uptake have also been demonstrated in *Coffea* spp., a highly mycotrophic species (Andrade et al., 2009). The management system may impact AMF diversity in soils and coffee roots, with monoculture showing a decline in AMF abundance compared to more diversified coffee production systems (Muleta et al., 2007; De Beenhouwer et al., 2015). In a recent study of 25 coffee farms in Costa Rica, which ranged from organic management with high shade and no chemical fertilizers to conventional management with minimal shade and high N fertilization, shifts in AMF abundance and diversity were related to soil nutrient availability and shade (Aldrich-Wolfe et al., 2020). The impact of coffee management intensity on AMF community composition has also been reported for coffee plantations in countries such as Ethiopia, Mexico, and Colombia (De Beenhouwer et al., 2015).

Soil macrofauna is considered another good indicator of soil quality, involved in ecosystem services contributing to the formation of ecological niches and favorable microclimates that increase the diversity of soil microbiota (Sofo et al., 2020). In Colombia, coffee plantations under full sunlight and intensive management and shaded coffee plantations with organic management showed marked differences in soil macrofauna composition and abundance, with higher densities of Oligochaeta (earthworms), Diplopoda (millipedes), and Blattodea (cockroaches and termites) in the latter, which improved soil fertility characteristics (Suárez et al., 2019). Earthworm diversity and abundance were higher in organic than in conventionally managed coffee farms in the state of Espírito Santo, Brazil (Santos et al., 2018). Similar results comparing minimal tillage and conventional coffee plantation were also reported in the state of Paraná, Brazil (Bartz et al., 2009). Complementarily, practices such as the application of herbicides and copper-based fungicides, more commonly used in conventional coffee plantations, are detrimental to earthworms, potentially reducing water infiltration and net C mineralization rates (Bartz et al., 2009; García-Pérez et al., 2014).

Soil quality reflects coffee bean production and quality, with implications for bean biochemical characteristics and beverage quality (Vaughan et al., 2015; Yadessa et al., 2020; Prates Júnior et al., 2021). In addition to the role of soil biota on nutrient cycling, pathogen suppression, and their beneficial interactions with coffee plants, soil biota may influence the coffee bean microbiome, and act as a source of microbes that can positively or negatively influence postharvest bean processing (Hameed et al., 2020; Vale et al., 2021). In the coming years, high-throughput sequencing technologies will unveil the high diversity and the many key processes microbe play in soil-plant-environment interactions in both natural and agricultural systems (White et al., 2017; Duong et al., 2020; Fulthorpe et al., 2020).

Use of biofertilizers and microbial inoculants in coffee production

Microbes with the potential to be used as biofertilizers are an environmentally friendly alternative to the continued inputs of mineral fertilizers. Biofertilizers promote coffee growth by improving plant mineral nutrition, producing phytohormones, and/or inhibiting plant pathogens and pests (Duong et al., 2020). In coffee nurseries, the seedling formation stage is critical to guaranteeing the production of vigorous and healthy plants and improving seedling transplantation and establishment in the field. As a perennial crop, coffee trees may remain productive for 30-35 years, depending on the cultivar, crop management, and edaphoclimatic conditions. Additionally, seedling quality is essential to the establishment of a coffee plantation. To promote plant health and reduce the time for transplantation, microbial inoculants have been mostly used during the coffee seedling formation stage in nurseries or field transplantation. The plant growth-promoting microorganisms in the inoculants include either bacteria or fungi such as AMF (Tristão et al., 2006; Muleta et al., 2013; Duong et al., 2020). Arbuscular mycorrhizal fungi (AMF) inoculation at the nursery stage has been shown to reduce the negative effects of coffee leaf rust infection after transplantation, indicating their potential as agents for biological control (Vallejos-Torres et al., 2023).

Microorganisms (either bacteria or fungi) from the coffee rhizosphere, endosphere, or coffee soils have been screened and isolated for potential use as microbial inoculants (Duong et al., 2020, 2021). For example, phosphobacteria species associated with the rhizosphere in natural coffee forests in Ethiopia can solubilize poorly soluble phosphates, a trait of interest, by producing organic acids (Muleta et al., 2013). Furthermore, strains of *Pseudomonas* spp. and *Bacillus* spp. isolated from the rhizosphere of *C. arabica* showed antagonistic effects on the fungal pathogens *Fusarium xylarioides* and *F. stilboides*, which cause coffee wilt disease, and were recognized as promising biocontrol agents (Muleta et al., 2007). The inhibitory effects of those strains were mainly related to the *in vitro* production of siderophores and hydrogen cyanide or to enzyme activities such as chitinases, proteases, and β-1.3-glucanases (Muleta et al., 2007).

Endophytic bacteria isolated from coffee roots and seeds in Vietnamese plantations have shown *in vitro* antifungal and nematocidal activities against coffee pathogens *F. oxyspurum* and the parasitic nematodes *Radopholus duriophilus* and *Pratylenchus coffeae*, respectively (Duong et al., 2021). However, further *in planta* studies should still confirm their efficiency for pest control (Duong et al., 2021).

Among fungal candidates, *Cladosporium* spp., from the Hypocreales order, isolated from coffee plantation systems in El Salvador, could be used to promote plant growth or induce disease resistance in coffee plants (Rao et al., 2020). At the time of sowing, the inoculation of another ascomycete, *Aspergillus niger*, promoted root and shoot growth of *C. arabica* seedlings. The benefits observed were not directly related to its phosphate-solubilizing ability but to additional mechanisms such as phytohormone production (Araújo et al., 2020). *A. niger* also stimulated coffee seed germination and showed potential as a biocontrol agent for the collar rot in coffee caused by *Rizotocnia solani* (Araújo et al., 2020).

Together, these findings may extend the use of indigenous microbes as microbial biofertilizers. Currently, the agro-biotechnology industry is showing growing interest in developing products based on beneficial plant-microorganism interactions, with a broad repertoire of inoculants for cash crops such as coffee (Saad et al., 2020). However, although great progress is evident, there is still a disconnection between academia, industry, and farmers supporting the benefits of microbiome-based products on plant health in various crops and environmental conditions (French et al., 2021).

Urochloa intercropping with coffee

In Brazil, coffee is conventionally grown under the full sun, without weeds in the interrows (bare soil), requiring periodic weed control (Favarin et al., 2018). Under this system, the soil reaches high temperatures during the summer, leading to the death of the roots growing between the lines, which can aggravate the effects of water stress. This short-term sustainable system leads to carbon loss and greater dependence on inputs such as fertilizers, irrigation, and herbicides.

Green manure in coffee systems (inter-rows) is one step towards sustainability in coffee production. This management form is not new; legumes were initially chosen incorporate N into the soil (Paulo et al., 2001; Ricci, 2005; Coelho et al., 2013; Mendonça et al., 2017). Incorporating of into the soil can be quite significant depending on the legume species, as is the case of *Leucaena leucocephala*, with 400-600 kg ha^{-1} (Ricci, 2005). Furthermore, the growth habit of the legume species and the size of plants may require different types of management, including pruning, which can increase production costs. The use of legumes as a source of N and organic matter is discussed in "Organic management of coffee". Herein, we will focus on recent studies with coffee × grasses systems, particularly on species of the genus *Urochloa*. As is the case with legumes, the use of *Urochloa* species in intercrop cultivation is related to improvements in physical, chemical, and biological soil characteristics, such as erosion control, increased organic matter and biological activity, fertility, and soil aggregate formation (Boddey et al., 1996). However, improving soil fertility and nutrient cycling are long-term processes that demand coffee farmers pay attention to the adequate supply of nutrients to coffee consumers (Aguilar et al., 2003). The use of these grasses with other cultures, mainly annual, was comprehensively covered in a recent report (Baptistella et al., 2020). To facilitate the reading of the text, we will use the term *Urochloa* for the various species of the genus.

Urochloa species are perennial grasses grown in Brazil mainly as pastures or in consortium with annual plants, such as maize (Rao et al., 1995; Baptistella et al., 2020). *Urochloa* offers rapid growth and genetic variability for adaptations to water restrictions and flooding, low fertile soils, soil acidity, and diseases (Miles et al., 2016; Almeida et al., 2017). *Urochloa* species stand out from other cover or interlayer crops, such as crotalarias (*Crotalaria* spp.) and millet (*Pennisetum* spp.), mainly on account of the large biomass they produce (Wutke et al., 2014).

In crop rotation or as intercrop, *Urochloa* can accumulate per year up to 16 t ha^{-1} of dry mass of leaves and straws (Bernardes et al., 2010; Costa et al., 2016; Miguel et al., 2018) and has been related to a significant potential availability of nutrients, such as 100 kg ha^{-1} of N and 130 kg ha^{-1} of potassium (Baptistella et al., 2020). Biomass accumulation in roots varies between 5.3 to 38 t ha^{-1} (Razuk, 2002; Apolinário et al., 2013; Saraiva et al., 2014). In contrast, this large underground biomass accumulation is related to an impressive vigorous, deep, and superficial root system, which explores a large volume of soil. This allows for the cycling of nutrients not used by the main crop, which in the case of coffee, has a less dense and more superficial root system (Defrenet et al., 2016). The interaction of the *Urochloa* root system with the soil microbiota can also help form and stabilize soil aggregates and increase porosity. *Urochloa* is highly colonized by mycorrhizas, which, in part, explains their ability to grow in low-fertility soils (Smith and Read, 2010; Leite et al., 2019; Baptistella et al., 2020). This characteristic is exciting since coffee is also quite colonized and depends on mycorrhizas to acquire nutrients, mainly P, and contributes to the positive water status of coffee plants (Andrade et al., 2009, 2010). Moreover, several authors have shown that the roots of *Urochloa* were active and capable of absorbing nutrients even at a depth of 1m in the interrow of coffee and that they were capable of mobilizing part of the non-readily available P, recycling enough P to satisfy the demand for high coffee yields (Baptistella et al., 2022).

With such an ability to accumulate biomass, the *Urochloa* × coffee system has significant potential for sequestrating atmospheric carbon. A study of a 16-year-old coffee plantation, with a close space between rows (2.5 × 0.80 m), intercropped with rubber trees (double rows of 4.0 × 2.5 m separated by 16 m) showed that the coffee plantation alone had an average C stock of 148.34 t ha^{-1} per year, while in the coffee-rubber tree system, this average was 195.6 t ha^{-1} per year (Zaro et al., 2020). Carbon stock and tree biomass were estimated from 20 family farmers cultivating coffee under agroforestry systems, where 95 species were identified (Gonçalves et al., 2021). Projections showed that the total mean of carbon stock in two- and 16-year-old coffee agroforestry systems was 1.38 t ha^{-1} and 59.69 t ha^{-1} of C, respectively. Taking into account that *Urochloa* can accumulate per year up to 16 t ha^{-1} of the dry mass of leaves and straws (Bernardes et al., 2010; Costa et al., 2016; Miguel et al., 2018) and between 5.3 to 38 t ha^{-1} of the dry mass of roots (Razuk, 2002; Apolinário et al., 2013; Saraiva et al., 2014), in about 4-5 years *Urochloa* should easily reach the values reported for the coffee × rubber tree system. This estimation is reduced to only one year when the values obtained by family farmers are taken into consideration, pointing to the great potential of *Urochloa* as an intercropping culture with coffee.

Coffee-*Urochloa* management

Urochloa growth is impaired by low light intensity. Thus, it is important to consider the spacing between the coffee lines, their orientation to the daily path of the sun, the height of the coffee varieties, as well as pruning management (Baptistella et al., 2020). Dwarf coffee varieties are predominant in Brazil, most carrying the Caturra allele (Carvalho et al., 1984). However, depending on the region and fertilizer management, even these varieties can reach two meters in height.

Urochloa is planted in the coffee inter-row 0.5 m to 0.7 m away from the coffee canopy projection, with weeds initially controlled by herbicides. Then, after the first cut of *Urochloa* shoot, its residues serve as mulch to control these weeds (Favarin et al., 2018). This distance avoids competition for nutrients, although coffee farmers use spread fertilizers throughout the area (Mazzafera, personal observation). The logic of this procedure is that the nutrients absorbed by *Urochloa* will be made available to coffee when the grass aerial part is cut. In addition, certain applied nutrients, such as N, may have a higher recovery when fertilization is applied to the total area, being divided between coffee and *Urochloa* (Pedrosa et al., 2014). *Urochloa* shoots cutting frequency depends on the management but varies from three to five per year in the rainy season. Using ecological mowers allows part of the shoot residue to be directed under the coffee canopy. The biomass deposited maintains the superficial soil moisture and promotes fine root development (Pedrosa et al., 2014; Martinelli et al., 2017; Favarin et al., 2018; Franco Júnior et al., 2019; Resende et al., 2022). The inter-row cultivation of *U. decumbens* with coffee has favorable effects on soil physical and chemical characteristics, which leads to better development of the coffee root system (Siqueira et al., 2015) and increased water storage capacity under irrigation (Rocha et al., 2016). These changes also led to increased production. *Urochloa* was able to potentialize the effect of N fertilizer and coffee husk use, increasing coffee productive nodes, yield, and soil moisture (Voltolini et al., 2022). Despite the reported positive aspects of *Urochloa* intercropping on the coffee root development, there is still a lack of information on the density and depth of coffee root growth and the lateral growth towards the middle of the coffee inter-row. Increased lateral growth is attractive because it would improve nutrient use efficiency. Unfortunately, few studies have addressed the whole coffee root distribution system, and information on lateral growth is controversial. Lateral roots are reported to remain mainly under the projection of the canopy (Inforzato and Reis, 1963) or can go beyond that (Saíz et al., 1961), going up to half the coffee row (Franco and Inforzato, 1946).

Certain studies did not explicitly aim at evaluating the use of *Urochloa* as a coffee intercrop, but instead at weed control during the coffee planting. Although young coffee plants can suffer competition and have reduced growth (Araújo et al., 2012), significant benefits of intercropped *Urochloa* with coffee lines have also been described (Siqueira et al., 2015). The comparison of weed control methods, including mechanical, chemical (herbicide), and vegetation cover methods (like *U. decumbens*) showed that in addition to controlling weeds at the two depths analyzed (0-15 cm and 15-30 cm), there was an increase in soil pH, Ca and Mg contents, the sum of bases and cation exchange capacity, and organic matter content. In another study, the use of *U. decumbens* to control weeds did not cause soil compaction in three soil layers compared with mechanical or chemical methods (Pais et al., 2011).

The incorporation of organic matter in the soil contributes to the colonization of the rhizosphere by microorganisms, which interact with roots and influence the availability of nutrients for plants (Andreote et al., 2014; Andreote and Silva, 2017). Furthermore, the soil microbiota may improve soil physical characteristics, such as the formation and stabilization of aggregates (Bardgett et al., 2014). Urochloa also seems to improve soil microbiota when intercropped with coffee. The enzymes β-glucosidase, arylsulfatase, and acid phosphatase, which are bioindicators of soil microbial activity, increased significantly in response to the presence of *Urochloa* in coffee plantations (Rodrigues et al., 2022).

Pests and diseases in the coffee-*Urochloa* system

There are several advantages of intercropping *Urochloa* with coffee: a) increase in soil organic matter content with a consequent increase in cation exchange capacity (CEC) and water retention; b) higher glomalin in the soil, a protein secreted by mycorrhizal fungi, which allows for the formation and stability of soil aggregates (Singh et al., 2013; Holátko et al., 2021); c) formation of soil pores originated by the death of roots which improves the diffusion of gases; d) decrease in soil compaction; e) bioactivation of the soil by microorganisms due to higher organic matter; f) increased soil water retention; g) decrease in temperature in the first layers of the soil (Favarin et al., 2018). Conversely, Urochloa plants are hosts of nematodes from the genus *Pratylenchus*, which cause severe damage to coffee plants (Inomoto et al., 1998, 2007; Mazzafera et al., 2004). However, damage in coffee commercial plantations due to the transfer of nematodes from Urochloa have not yet been reported, presumably because the significant addition of organic matter from the grass into the soil exerts a nematode population control (Widmer et al., 2002). Moreover, *Urochloa* reduced the populations of *Meloidogyne* spp. and *Helicotilencus* spp. when intercropped with coffee (Franco Júnior et al., 2022).

An important consequence of maintaining moisture in the soil under the coffee canopy by *Urochloa* shoot residue is control of the coffee berry borer (*Hypothenemus hampei*). This insect can cause annual economic losses worldwide more than US$ 500 M (Johnson et al., 2020). In Brazil, the world's leading coffee producer, the damage is estimated to be in the range of US$ 215-35 M (Oliveira et al., 2013). Fruit infested by insects and fallen before or during harvest remaining on the ground from one year to another maintain the potential for infestation for the following year (Guerreiro Filho and Mazzafera, 2003; Johnson et al., 2020). Because the soil moisture is maintained at a high level by *Urochloa* residue, these seeds germinate or rot, thereby decreasing the potential for future infestation (Mazzafera and Baptistella, personal observation).

Another possible advantage of intercropping *Urochloa* with coffee could be control of the leaf miner *Leucoptera coffeela*. The coffee leaf miner infestation may cause severe leaf loss to decrease productivity (Dantas et al., 2021). Their larvae form galleries inside the leaves and eat the mesophyll cells further inducing leaf fall. This pest spreads mainly in the dry season. Thus, maintaining a microclimate with higher humidity may positively affect pest control. Additionally, the maintenance of *Urochloa* between the coffee lines may enhance the presence of natural enemies of the coffee leaf miner. However, these hypotheses still need to be evaluated. Until 1970, problems caused by the coffee leaf miner were rare because of the effectiveness of natural enemies and the larger spacing between the coffee lines than that used today (Dantas et al., 2021). The smaller spacing used nowadays could positively affect maintaining a wetter microclimate within the crop. Moreover, the cultivation of coffee in drier regions may have favored pest population growth, greater infestations, and, consequently, more significant losses (Dantas et al., 2021). In addition, the increase in pest chemical control may have harmed the population of natural enemies of the coffee leaf miner.

Yellow leaf rust (orange rust), caused by the fungi *Hemileia vastatrix*, is the main coffee disease (Silva et al., 2006). Reduced coffee yield may be significant in severe disease attacks. The fungi infect the lower surface of the leaves, producing a large mass of uredospores which leads to early and severe leaf fall. Because spores need water in a liquid state to germinate, orange rust infects coffee mainly during the rainy season and the wetting time becomes an important factor for disease spread (Rayner, 1961; Kushalappa, 1989; Zambolim, 2016). Irrigation and interrow space can also increase disease severity because of higher humidity inside the crop canopy (Paiva et al., 2011; Custódio et al., 2014). High-density plantation and shading coffee plants with trees stimulate spore germination by extending leaf wetness duration (Avelino et al., 2004). In the same way, the *Urochloa*-coffee consortium might favor a more extended leaf wetness period during the mornings. However, like coffee management practices may affect the disease success (Avelino et al., 2004), the management of *Urochloa*, specifically the number and height of plants at cutting will interfere with humidity conditions and disease susceptibility. Unfortunately, information on this issue is still lacking.

Coffee shading

The advent of climate change resulting from global warming is a reality that cannot be denied. Extreme temperatures, drought, excessive rain, and other climatic disorders characterize such changes. Agriculture is likely one of the human activities most impacted by these changes (Camargo, 2010; Zullo et al., 2011). Therefore, adopting cultivation techniques that mitigate these effects and allow the sustainable production of coffee is a great challenge for coffee growers in the coming decades.

Although *C. arabica* has great phenotypic plasticity, its growth and development are limited by temperature and water availability, especially in critical phenological phases. Adequate development and production occur in regions with average temperatures below 22 °C and above 19 °C (Camargo, 1985). High radiation and temperatures can exhaust the reserves of Arabica trees and induce photo-oxidative damage to the leaves (Matta, 2004). Therefore, climate changes are expected to severely impact traditional cultivation areas, where coffee production will tend to migrate to higher altitudes with milder temperatures (Camargo, 2010). In 2014, for example, a prolonged drought was disastrous for Brazilian coffee farming, causing significant yield losses (Vegro and Almeida, 2020).

Shading is one of the measures for mitigating the effects of climate change and guaranteeing the maintenance of microclimate conditions favorable to producing Arabica coffee. Shade-grown coffee in consortium with trees can confer lesser environmental risks and, at the same time, add value to the product. This is a regular practice in countries in Central and South America and Africa, as well as in Mexico, India, and Indonesia (Farfán, 2014). A study developed from Apr to Nov under Brazilian conditions at São Sebastião do Paraíso, a traditional coffee producer area located 950 m a.s.l. (above sea level), verified that up to 30 % of shade reduced total radiation, temperature and wind speed compared to full sun cultivation. In addition, in the driest period of the year, relative humidity was superior under shaded grown systems (Coltri et al., 2019).

A recent study that used 19 global circulation models to predict climatic conditions in the major coffee production area in southeast Brazil by 2050 has shown that the annual mean air temperature is expected to increase 1.7 ± 0.3 °C (Gomes et al., 2020). Such a temperature rise would result in a 60 % reduction in the areas suitable for coffee plantations, especially between 600 and 800 m a.s.l. However, using agroforestry systems with 50 % shade cover would permit maintaining 75 % of the area suitable for coffee production (Gomes et al., 2020). Nevertheless, shaded cultivation systems vary widely, from situations where coffee plantations are established in native forests thinned by selective removal of trees to consortiums with only one or two tree species and through coffee areas where exotic trees are used. Thus, regional studies are necessary to profit from the advantages of agroforestry or shaded systems, particularly climatic and edaphic conditions.

C. arabica origin center in Ethiopia has altitudes between 1600 to 2000 m a.s.l., a humid climate with a dry season lasting two to four months. The average temperatures range from 17 to 19 °C in the coldest month and from 22 to 26 °C in the warmest month (Camargo, 1985). Under these conditions, coffee grows in the lower strata (below 5 m) of forests with four strata, the upper two reaching 10 to 40 m (Caramori et al., 2004). Moreover, in these circumstances, coffee produces few flowers and spends only the surplus of photosynthates for fruiting, indicating that the ability to grow/develop in low light is a more important survival strategy than seed production (Cannell, 1985).

Under excessive shading, coffee trees have morphological and physiological changes, such as fewer and larger leaves, a reduction in the number and growth of productive branches, which present fewer nodes per branch and fruit per node (Campanha et al., 2004; Jaramillo-Botero et al., 2006; Morais et al., 2006; Ricci et al., 2006). Leaves grown under shade have lower specific weight, thinner cuticles, less N per unit area, fewer thylakoids per granum and grana per chloroplast, and higher concentrations of protochlorophyll, chlorophyll *a*, and chlorophyll *b* (Fahl et al., 1994; Morais et al., 2004). Compared to plants growing in full sunlight, shaded coffee plants have leaves with thinner cell walls, thicker epidermal cells, larger intercellular mesophyll spaces, chloroplasts with altered shapes, and lower stomatal index (Morais et al., 2004; Nascimento et al., 2006; Gomes et al., 2008). As expected, these changes can be accompanied by reductions in photosynthetic rates, stomatal conductance, and transpiration (Fahl et al., 1994; Morais et al., 2004). Thus, shading coffee can be detrimental to productivity.

Conversely, there is evidence that shade trees increase the proportion of diffuse light under their canopy and that the light use efficiency by coffee can increase, compensating partially for the reduction in the absorbed photosynthetically active radiation (Charbonnier et al., 2017). The level of shade must be such that the reduction in production due to competition for light, water, and nutrients among the shading trees and the coffee plants is compensated by the reduction in the biennial fluctuation of coffee production, which is a characteristic of full sun coffee cultivation (Caramori et al., 1995). Additionally, the shade the trees provide may attenuate damage to the leaves caused by excess of light. (Caramori et al., 1995).

The arrangement of the plants, the shade density, and the system management also vary widely. While relatively stable yields were obtained within 25 to 35 % of shading (Baggio et al., 1997), the use of light windows to guarantee coffee plants will receive unfiltered light corresponding to 20 to 60 % of photosynthetically active radiation (PAR) is also recommended (Caramori et al., 2004; Farfán, 2014).

In Colombia, it has been suggested that the shading must be proportional to the hours of sun brightness, a maximum of 45 % and 20 % of shade when the sun brightness is in the range of 2300 h per year and 1000 h per year, respectively (Farfán and Jaramillo, 2009). The former defines cultivation systems as thin or heterogeneous shading (less than 25 % of shading), moderate shading (25 to 45 % of shade), and dense or homogeneous shading (more than 45 % of shade - Farfán, 2014).

In addition to the effects of the percentage of light blockage described in the paragraph above, the competition for water and nutrients between the coffee tree and the shadowing tree species have to be considered. Species with a superficial root system will compete for water with coffee plants in periods of unfavorable water balance, as observed under the dry Brazilian winter conditions (Neves et al., 2007; Moreira et al., 2018), especially in poorly structured soils. Special attention needs to be given to the choice of shade species considering, in each case, the main environmental factor to be mitigated by them (Caramori et al., 2004).

Shading alters the incidence and distribution of light inside the coffee canopy, and buffers climate fluctuations, creating a microclimate suitable for the sturdy development of coffee trees in full sunlight environments (Jaramillo-Botero et al., 2006). The leaves of the upper stratum intercept the incident radiation and alter the energy balance. The shading affects air temperature, relative humidity, and wind speed. Shading decreases the global incident radiation and the photosynthetically active radiation that reaches the coffee trees as well as the heat losses by irradiation on frosty nights (Morais et al., 2006). On frosty nights, the leaves of coffee plants under shade remain at temperatures between 1 and 4 °C higher than the external environment (Caramori et al., 1999), while the maximum temperature in coffee leaves shaded with pigeon-pea was up to 10 °C lower than that of plants grown in full sun (Morais et al., 2003). Macauba (*Acromia aculeata*) consortium with coffee is reported to attenuate both maximum and minimum air temperatures compared to full-sun coffee cultivation (Moreira et al., 2018). Excessive wind increases transpiration and aggravates water deficiency (Caramori et al., 2004). In addition, winds with speeds above 2 m s^{-1} can reduce photosynthesis and cause mechanical damage to the coffee leaves (Caramori et al., 1986).

In shaded coffee plantations, lower air, and leaf temperatures, reduced wind speed, and higher air relative humidity lead to a decrease in the vapor pressure deficit between the leaf and the atmosphere and in transpiration. With such a condition in force, the influx of CO_2, as long as the stoma remains open, is not accompanied by water vapor loss, increasing water use efficiency. This greater water use efficiency translates into increased production and plant longevity, especially in regions subjected to relatively long periods of drought or with high evaporative demand (Matta, 2004).

The biennial production of coffee occurs because vegetative growth is impaired in a high-productivity year, which decreases the number of fruiting nodes in the following year. The use of shade via afforestation reduces the emission of flower buds but minimizes the biennial cycle (Campanha et al., 2004; Morais et al., 2006; Jaramillo-Botero et al., 2010) and mitigates the exhaustion of reserves in years of high production.

Where shade reduces production (Campanha et al., 2004; Morais et al., 2006; Jaramillo-Botero et al., 2010; Santos et al., 2012), there is a lower demand for nutrients, particularly N, an increase in plant longevity, and a reduction in the production costs (Farfán, 2014). Nevertheless, it is essential to highlight that under moderate shade, the competition between shade species and coffee is minimized, and it is possible to have similar or higher yields than in full sunlight coffee (Soto-Pinto et al., 2000; Ricci et al., 2006; Moreira et al., 2018).

Growing coffee under shade protects the soil from excessive sunlight, reduces the impact of rain, and can improve soil moisture conservation (Lin, 2010). Shaded coffee orchards show less soil loss due to erosion (Geissert et al., 2017), especially on slopes above 20 %. The greater litter deposition generally forms a barrier to water and wind erosion and reduces soil temperature (Morais et al., 2006; Bote and Struik, 2011). In agroforestry systems, a reduction in soil bulk density, soil resistance to penetration, and soil content of dispersed clay can be observed (Aguiar, 2008). Water infiltration and the stability of soil aggregates also show improvement and since root trees can go deeper in the soil profile, there can be better cycling of nutrients (Melloni et al., 2018).

Such ameliorated soil microclimate conditions also become more favorable to the soil microbiota. Coffee trees shaded by *Grevillea robusta* (Bonfim et al., 2010) and *Araucaria angustifolia* (Melloni et al., 2018) had a higher percentage of colonization by mycorrhizae compared to coffee orchards in full sunlight. Similarly, a more significant presence of vesicular-arbuscular mycorrhizal spores in deeper soil layers in a coffee-agroforestry system compared with full sunlight coffee orchards (Cardoso et al., 2003).

Another advantage of growing coffee under shade is the possibility of producing better quality coffees (Melloni et al., 2018), potentially destined for the specialty coffee market. This has been attributed to increased bean sugar content (Souza et al., 2013). Under full sun greater bitterness and astringency of the beverage, higher contents of chlorogenic acids and trigonelline are related to incomplete fruit ripening (Vaast et al., 2006). Under full sunlight, the coffee fruit changes quickly from green to ripe, and if high temperatures and water deficit prevail, there could be a higher incidence of defective beans retained in a smaller sieve size, with a high percentage of empty fruit and a drop in the bean to husk ratio. Shade, in turn, slows down maturation and reduces production but can enhance the achievement of well-formed beans retained in sieves of greater size resulting in better-quality coffee (Ricci et al., 2006).

Unfortunately, it has not yet been possible to establish safe cause-and-effect relationships between radiation levels received by coffee plants and variables that affect the sensory attributes of coffee (Salazar et al., 2015). It has been observed that better quality under shade is related to higher altitudes, which can be attributed to a lower risk of water stress, reductions in temperature, and slower fruit ripening (Salazar et al., 2015). Lower-quality coffees are obtained at high altitudes and with high cloudiness; under such conditions, tree cover may be managed by pruning (Salazar et al., 2015).

In addition to *C. arabica*, shading has also been demonstrated to be a useful tool for other coffee species. The effect of shade in *C. canephora* cultivated in a robusta coffee region at 143 m a.s.l. was evaluated by means of multivariate analysis. The results are evidence of the consortium of *C. canephora* with *Gliricidia sepium* producing coffees with higher values of acidity and sweetness when compared with plants grown under full sun (Correia et al., 2020). The authors argue that this result could be related to the lower caffeine content in plants exposed to full sun, which affects the sweetness/bitterness relationship of the drink.

Organic management of coffee

The role of organic matter in soil fertility and using plant and animal waste to increase crop productivity is ancient knowledge. Roman writings have already described animal manuring, liming, green manure use, crop rotation, and mulch as important cultivation techniques (Kiehl, 1985). Nowadays, the importance of soil organic matter to maintaining soil microbiota and improving its physical and chemical properties is undeniable, especially under conditions of very weathered and low fertility soils as the Oxisols prevalent in certain regions of Brazil, which support extensive crop cultivation. However, modern agricultural practices have largely contributed to the oxidation of organic matter, loss of fertility, erosion, and salinization of many areas, as well as to the production of high volumes of waste and emission of greenhouse gases as a consequence, among others, of the use of synthetic nitrogenous fertilizers. The production, distribution, and application of 1 kg of synthetic N are responsible for 4.5 kg of CO_2 equivalent emission (Oliveira et al., 2014). A fraction of about 31.2 % of the N applied as urea (three top dressings a year) was lost by volatilization in coffee orchards located in the Lavras region, Minas Gerais, Brazil (Dominghetti et al., 2016). In contrast to the environmental risks of high-input agriculture, interest in food free of pesticide residues and sustainably produced has significantly increased over the last few decades. More recently, the possibility of C sequestration by increasing the soil organic matter and contributing to global warming mitigation stimulates organic food production.

Following this, high carbon sequestration in *C. arabica* agroforestry systems in southwestern Ethiopia has been reported (Niguse et al., 2022). The study was carried out in an area of 105 ha, located 1300-2552 m a.s.l., with mean annual rainfall between 1700 to 2200 mm, and minimum and maximum temperatures of 10 and 27 °C, respectively. Under such conditions, the authors verified a 254.9 to 321 t ha^{-1} of carbon sequestration considering aboveground and belowground carbon. Coffee plants were responsible for net carbon sequestration from 18.8 t ha^{-1} C to 48.5 t ha^{-1} C, about 12.8 % of total sequestered C in these agroforestry systems. These values were higher than those reported in other studies carried out in Guatemala, Mexico, and Indonesia. The authors have determined that various factors, including coffee species, management practices, and site factors such as climate and soil condition, among others, are responsible for the differences observed. Therefore, carbon sequestration in coffee agroforestry systems shows to be expressive, and carbon coffee credits could be a strategy to encourage this environmentally friendly system.

Worldwide, organic coffee cultivation is estimated at 8 % of the total crop planting area, yielding 447 metric tons of fruit in 2016 (Lernoud et al., 2017). Mexico, Ethiopia, Peru, Indonesia, and Tanzania are the leading producers of organic coffee (Lernoud et al., 2017). The market for certified organic coffee has doubled in the last five to six years (Pião et al., 2020). However, only 3 % of world coffee production meets this certification requirements, including avoiding practices potentially harmful to the environment. Deforestation, agrochemicals, and synthetic nitrogenous compounds are prohibited, and soil conservation practices are required. As a rule, it is an expensive certification process, but the premium compensates for the low productivity often observed under these production systems. Family farmers in Espírito Santo, Brazil, depend heavily on receiving the premiums for organic cultivation to make their farm production economically viable (Siqueira et al., 2011). Furthermore, the authors stress the challenge and the need to improve technical efficiency in such cultivation systems. Others have reached similar conclusions after studying organic coffee farms in Zona da Mata, Minas Gerais, Brazil (Carmo and Magalhães, 1999).

More studies are necessary to recommend suitable cultivars for organic production in different coffee regions. According to Moura et al. (2014, 2017), the low productivity of organic orchards is due, in part at least, to the fact that the cultivars in use are the same as those used by conventional cultivation systems and, in general, are equally susceptible to the rust fungus *H. vastatrix*. These authors have studied the adaptability and stability of 30 coffee cultivars under an organic system in six different environments in the state of Minas Gerais, Brazil and have determined that five cultivars (IBC Palma 1, Catucaí Amarelo24/137, Sabiá 708, Oeiras MG 6851, and H 518) were widely adapted, stable, productive, and suitable for organic cultivation in this region.

Supplying the nutrients required to achieve high coffee production via organic fertilization has been challenging, especially in single crops under full sunlight, which stimulates flowering. Therefore, both the source of nutrients and the nutrient use efficiency by plants should be considered in the organic management of coffee. This opens new research areas, such as growing coffee under organic cultivation.

Studies on coffee mineral nutrition show that productive crops extract and export considerable macro and micronutrients from the soil. For macronutrients, there was an average extraction of 490, 330, 220, 66, 43, and 30 kg ha^{-1} N, K, Ca, Mg, S, and P, respectively, by 5,000 plants per hectare stand during 55 months of cultivation and with accumulated production of 4,650 kg ha^{-1} (77.5 60-kg-bags) of processed coffee. For micronutrients, the values reached 1,600 g ha^{-1} of B, 770 g ha^{-1} of Zn, and 550 g ha^{-1} of Cu. Of this amount, 46 % of K, 37 % of P, 25 % of N, 19 % of S, 18 % of Mg, 5.5 % of Ca, 20 % of Cu, 7 % of B, and 6 % of Zn were accumulated in the fruit, showing that nutritional requirement is strongly linked to production. To maintain production sustainability, at least 1.58 kg of N, 1.96 kg of K, 0.16 kg of Ca, 0.15 kg of Mg, 0.14 kg of P, 0.10 kg of S, 1.44 g of B, 1.42 g of Cu, and 0.60 g of Zn must be returned to the system for each 60-kg-bag of processed coffee produced (Martinez et al., 2019).

In organic coffee production systems, fertilization should be applied by recycling organic material whenever possible. Several organic sources of nutrients have been used (coffee straw, crop residues, manure, animal beds, organic compost, castor cake and bran, coal mill, ash, and blood and bone meal) and mixed in varying amounts with certain mineral sources accepted by certifiers (limestones, rock phosphates, thermos-phosphates, potassium sulfate, double potassium, and magnesium sulfate) according to the chemical characteristics of the soil and requirements of the plants. Combining several materials to provide adequate amounts and proportions of nutrients at the different stages of growth and production, considering the distinct spatial distribution of coffee orchards, is a complex task. In addition, fertilization depends on the decomposition speed of the organic material applied.

The doses of organic fertilizers are often calculated based on the demand for N, which in many cases, such as cattle manure or composting material, poses a challenge to obtaining and handling the high volumes required (Martins Neto, 2016). Chicken manure and poultry litter mixed with rice straw, coffee husks, and peanut straw figure among the most commonly used organic materials (Matiello et al., 2015).

Nutritional problems have been reported as being responsible for organic's low productivity compared to conventional cultivation systems (Paulo et al., 2001, 2006; Moreira et al., 2014; Cardoso et al., 2018a).

Although similar yields were also obtained under both systems, conventional systems have often been changed to organic to benefit from the nutrient reserves available in the soil (Theodoro et al., 2009).

Synchrony is the key to obtaining success in organic production systems. The nutrients in the different combinations and doses of crop residues, compost, manure from animal production, and green manures must be available when coffee plants require (Farfán, 2014). The sources chosen must be applied in advance to the mineralization peak and must have a C/N ratio between 15 and 30, which can curb further N immobilization. Generalizations are tricky because, in addition to the N concentration and C/N ratio, temperature, humidity, and aeration are variable factors that influence soil microorganisms and thus control organic matter decomposition.

One of the critical bottlenecks for adequate nutrition of coffee plants in organic production systems is their high N demand - between 2.5 and 20.0 t ha^{-1} of dry matter, depending on the organic source (Ricci, 2005; Fernandes et al., 2013a, b). The applied doses are elevated as organic fertilizers generally have a low N concentration.

As mentioned above, intercropping with legumes fixing atmospheric N_2 has been studied for a long time as an alternative means of N supply. However, because of the new approaches and technology adopted by coffee growers, legumes in coffee plantations are still under study. It should also be kept in mind that the low C/N ratio of legumes facilitates their fast degradation due to intense soil microbial activity in tropical soils (Matos et al., 2011; Araujo, 2015; Cardoso et al., 2018b). Thus, legumes should be seen mainly as a source of N instead of C (organic matter). For *Canavalia ensiformis* and *Dolichos lablab*, the N mineralization rate was slower than the decomposition of the dry mass and was subject to reduction over time (Araujo, 2015). In this regard, grasses seem to be a better choice, although intercropping cash crops with legume and *Urochloa* species may improve the C/N ratio and benefit the system (Fisher et al., 1994).

The amount of N supplied by green manure is variable (Araújo, 2012). Such variability is attributed to: a) the age at or phenological phase in which the legumes are cut; b) whether or not the regrowth is managed; c) the sowing time and planting density of the legumes, and d) the population and spatial arrangement of the coffee trees.

Based on the dry matter produced and its N content, Ricci (2005) reported the contribution of 444 kg ha^{-1} of N in two cuts by *Crotalaria juncea*. Araújo and Balbino (2007) reported that 59, 197, 165, and 183 kg ha^{-1} of N were contributed by *Cajanus cajan* cut at 120, 150, 180, and 210 days after sowing, respectively. Barrela (2010) verified that 2.35, 23.59, 47.24, and 71.52 kg ha^{-1} of N were incorporated into the system using *C. ensiformis* cut at 30, 60, 90, and 120 days after sowing, respectively.

In several studies, however, N input to the system was proportional to the accumulation of dry mass by green manures, but, contradictorily, this may be the reverse for coffee. The difficulty in synchronizing the demand for N by coffee trees and the cutting and releasing of N by intercropped green manures affects coffee productivity. With time, Barrela (2010) observed a drop in coffee production in the consortium with *C. ensiformis* and *Dolichos lablab*. While the consortium made nutrients, mainly N, available for coffee trees, it created competition for resources (e.g., water, light, and other nutrients) between the intercropped species (Barrela, 2010).

The rate of N accumulation in coffee fruit increases up to six months after anthesis (Fenilli et al., 2007). Laviola et al. (2009) found that in orchards located 720 m a.s.l., 36 % of N is accumulated in the fruit during the rapid expansion phase and 47 % in the grain filling-maturation phase. Moreover, the maximum N daily accumulation rate occurred during the rapid expansion phase, at 134 days after the anthesis (Laviola et al., 2009). Bearing this in mind, Cardoso et al. (2018a, b) studied the growth, decomposition, and mineralization of N in *C. ensiformis* and *D. lablab* intercropped with coffee in an organic production system. They inferred that to guarantee 50 % of the available N in Nov/Dec (rapid expansion of the fruits), the green manure would need to be cut at the end of Sept. In the climatic conditions of Zona da Mata, Minas Gerais, Brazil, whose winter is cold and dry, it would not be possible to anticipate the sowing of green manure to produce biomass sufficient to meet the N demand of coffee in such a phase. The sowing of the green manure is thus recommended as soon as the rainy season begins, with the cut at 90 days after sowing, which would provide part of the N necessary for the grain filling-maturation phase and for the growth of the coffee tree. Consequently, the annual green manures would complement mineral or organic fertilization. Supposing the leguminous sowing in Oct and the cutting after 90 days in Jan, and considering the observed contribution of 121.60 kg ha^{-1} of N by *C. ensiformis* and 65.68 kg ha^{-1} by *D. lablabe*, there would be approximately 55 kg ha^{-1} and 37 kg ha^{-1} of N available for the coffee intercropped with *C. ensiformis* and *D. lablab,* respectively, during the grain filling phase in Feb (Cardoso et al., 2018a, b). The authors found that green manure allowed for a 50 % reduction in the dose of organic fertilizer. Araujo (2015) observed reductions of the same order with the intercropping of *C. ensiformis* with coffee.

Experiments with ^{15}N have been used to quantify how much of the biologically fixed N is transferred to the coffee tree. Martins Neto (2016) fertilized potted coffee plants with *C. juncea* marked with ^{15}N. In 18-month-old plants that received marked *C. juncea* at 3 and 15 months after transplanting, the contribution of green manure to N nutrition of coffee was highest between 157 and 168 days after the supply. The maximum contribution of green manure was between 18.55 % and 19.44 % of total N. The total amount of N derived from green manure increased with the age of the coffee tree, and its partition was higher in the leaves, followed by the branches and roots.

In the field, Araújo et al. (2013) used organic compost-based fertilizer in quantities sufficient to supply 25, 50, 75, and 100 % of the N requirement for the coffee plant. They supplemented it with 450 g of dry *C. juncea* labelled with ^{15}N at 11 and 22 months after planting. These authors observed that until flowering, there was no effect of supplementation with *C. juncea*. However, after the beginning of the reproductive period, the application of *C. juncea* approximately two months after organic fertilization provided 9.2 to 17.9 % N in coffee leaves. Mendonça et al. (2017) studied the contribution of the legumes *Arachis pintoi*, *C. cajan, Calopogonium mucunoides*, *Crotalaria spectabilis*, *D. lablab, Stizolobium deeringianum* and *Stylosanthes guianensis* in supplying N to the coffee tree in eight coffee locations in Zona da Mata, Minas Gerais, Brazil. *C. cajan*, *C. mucunoides* and *C. spectabilis* transferred 55.8, 48.1 and 48.8 % of N from biological fixation to coffee plants, respectively. *C. cajan* had the largest contribution to biologically N fixed to the system (44.42 kg ha^{-1}).

Undoubtedly, organic fertilization of coffee must supply the nutrients required by the crop during its implantation, formation, and production phases. Different sources of nutrients must be combined to meet these requirements, making generalizations difficult. The consortium with N-fixing legumes provides a more sustainable and viable alternative to N mineral supply. However, certain open questions need to be clarified, such as the residual effect of the N supplied via organic fertilizers and green manures, and the progressive effect of increasing the soil organic matter. Long-term organic cultivation may increase the efficiency of nutrient use, which would perhaps allow for the reduction of fertilizer doses. Araújo (2012) highlighted the need for more knowledge about the relationship between the line spacing between coffee trees and the number of lines of legumes between those lines. Furthermore, suitable spatial arrangements are necessary for minimizing the effect of competition between species from the consortium. Managing legumes with successive cuts and regrowth should be investigated to provide greater amounts of N derived from biological N fixation in the sum of the harvested biomass.

Discussion

Soil quality and biofertilizers in coffee production systems

As soil organic matter conservation in coffee production systems, most of the studies we analyzed report significant increases in organic matter contents under agroforestry management and intercropping systems (Pimentel et al., 2011; Barrios et al., 2012; Rigal et al., 2020) when compared to intensive open coffee plantations or systems with practices such as tillage. The improvement effect of these management practices on soil organic matter is harnessed to the overall improvement of soil quality indices (Blackman and Naranjo, 2012) that, in several cases, have shown positive effects on coffee mineral nutrition, water acquisition, and grain quality. It is also highly probable that, as for other crops, coffee production will increasingly adopt biofertilizers to promote plant nutrition, growth, and health (Tristão et al., 2006; Muleta et al., 2013; Duong et al 2020). The number of studies showing potential for using microbes is notably higher in recent years, and the tendency to develop specific microbial-based commercial products for coffee is, in our opinion, high. The several reports we reviewed highlight the suitability of this array of practices that conserve soil quality and beneficial biotic interactions as a solution against the imminent negative effects of climate change and to more resilient coffee production systems, which can be more or less viable depending on the characteristics of the producer region.

Urochloa intercropping with coffee

Recently, coffee growers in Brazil have adopted intercrops between coffee and grasses from the genus *Urochloa* due to the many benefits added. In this review, we have covered the recent studies focused on coffee-*Urochloa* intercrop. As most of the benefits added to the system are related to the great amount of biomass both above and below-ground, proper management of *Urochloa* is essential to maximizing benefits to the system. It is important to consider: a) the height of the coffee variety and pruning to avoid shading; b) the distance of the grasses away from coffee rows to avoid competition; c) use of ecological mowers to cut and cover this space with residues, thus controlling weeds and promoting other benefits; and d) the frequency of these cuts throughout the year (Favarin et al., 2018; Baptistella et al., 2020).

Urochloa suppresses weeds (Pais et al., 2011; Siqueira et al., 2015), increases soil enzyme activity, soil moisture, water storage, promotes fine root growth and better coffee root development (Pedrosa et al., 2014; Rocha et al., 2016; Martinelli et al., 2017; Favarin et al., 2018; Franco Júnior et al., 2019; Resende et al., 2022; Rodrigues et al., 2022) which can lead to greater yields. *Urochloa* has great potential for increasing soil organic C inputs, but there have been no studies that have quantified that specifically for the intercrop; still, nutrient cycling by *Urochloa* can be enough to fulfil all of the coffee demand for certain nutrients such as P (Baptistella et al., 2022). *Urochloa* is highly colonized by mycorrhizas which could further impact coffee nutrition and water status (Andrade et al., 2009, 2010).

As regards coffee crop phytosanitary control, no problems were reported for *Pratylenchus* nematodes, and reduced populations of *Meloidogyne* spp. and *Helicotilencus* spp. were found (Franco Júnior et al., 2022). Furthermore, two of the main pests that attack coffee – coffee berry borer and leaf miner – may have their incidence and losses reduced and this could represent attractive economic savings on coffee production. On the other hand, including *Urochloa* could possibly increase coffee leaf rust incidence which would have to be counterbalanced by cutting frequency management or using of tolerant cultivars. Information on this issue is still lacking.

In summary, coffee-*Urochloa* intercrop is being used by farmers, but the literature still needs more information on many issues. Nevertheless, including *Urochloa* in the system can be an effective alternative for increasing coffee production sustainability and resilience as it represents a lower use of external inputs and a more efficient use of the resources in the area. *Urochloa* positively effects on soil chemical, physical and biological attributes, suppresses weeds and pests, and increases system nutrient cycling. However, we underscore the need for more research on this subject, especially regarding *Urochloa* and coffee root interaction, the effect of C inputs in soil, disease and pest control, and soil microbiology.

Coffee shading

Compared to full sun cultivation, shade coffee systems imply complex changes in the coffee-shade tree ecosystem which depend on the different relationships climate-plant-soil in each case. Therefore, it is difficult to make generalizations, and further regional studies in climatic and edaphic particular conditions are needed.

Shading attenuates incident radiation, buffers temperature fluctuations, and reduces wind speed, thereby reducing transpiration and increasing relative humidity. These changes reduce the risk of scald, frost, blight, and mechanical damage to the leaves (Jaramillo-Botero et al., 2006; Coltri et al., 2019). In addition, shading helps protect the soil from the impact of rain and keeps it moist for longer. The higher density of deep roots allows for better water infiltration in the profile. Greater litter deposition favors the improvement of soil properties and the development of a favorable microbiota.

Compared to full sun cultivation, coffee plants under shade present both morphological and physiological changes (Fahl et al., 1994; Morais et al., 2004; Nascimento et al., 2006; Gomes et al., 2008), which in areas with optimal climatic conditions for coffee cultivation can lead to a reduction in productivity, notably under excessive shading. Excess of shade leads to a reduction in the number of productive branches, number of nodes per branch, flowers and fruit per node, and consequently in productivity (Campanha et al., 2004; Jaramillo-Botero et al., 2006; Morais et al., 2006; Ricci et al., 2006). Under Brazilian conditions, several studies indicate that 30 to 35 % of shade is adequate. However, the optimal level of attenuation of incident radiation depends on the value of accumulated incident radiation.

Choosing adequate shade trees needs to be a matter of careful attention. Some could compete with coffee plants for water and nutrients, depending on the climate and depth of their root systems (Neves et al., 2007; Moreira et al., 2018). The selection of shade species should consider the main environmental factor to be mitigated. Pruning shade trees may be necessary during the floral bud differentiation or, most commonly, in the driest period of the year, when competition for water could occur. On the other hand, in dense stands, the increase in relative humidity may favor fungal diseases such as coffee rust (Avelino et al., 2004) if coffee cultivars resistant to *Hemileia vastatrix* races are not used.

It should always be remembered that shading-induced yield loss needs to be compensated by a reduction in biennial yield fluctuation, a reduction in wind damage, and a reduction in scald damage. Reduction in environmental risks, production costs, and the rise of enterprise profitability must also be considered.

The decrease in production, which often occurs under shade compared to full sun cultivation, also reduces the demand for nutrients, especially N, which reduces production costs (Farfán, 2014) and environmental risks. Under shade, there is greater efficiency in water use, greater longevity of coffee trees, and possibly better quality of coffee beans (Melloni et al., 2018). This level of quality is attributed to the slower maturation of the fruit, as reflected by a lower percentage of defective beans and beans with higher sugar content. Nevertheless, it can be concluded that studies do not show a clear cause-and-effect relationship between the levels of radiation received by the coffee tree and the sensory attributes of the coffee produced (Salazar et al., 2015).

The above discussion shows that coffee shading is an agronomic practice capable of providing greater sustainability to coffee production, which mitigates the effects of global warming in many traditional areas of cultivation of this Rubiaceae.

Organic management of coffee

It is well known that modern agricultural practices have contributed to increased productivity. However, at the same time, they have promoted the oxidation of organic matter, loss of fertility, erosion, and salinization of vast areas worldwide, in addition to the production of large volumes of waste and greenhouse gases (mostly the consequence of the use of synthetic nitrogen fertilizers). Nevertheless, as with many other plant species, in order to achieve high productivity, coffee trees require significant doses of nitrogen fertilizers, and data from the coffee region of Lavras, Brazil show losses of nitrogenous gases of 31.2 % of the N applied in top dressing as urea (Dominghetti et al., 2016).

On the other hand, using plant and animal residues as organic sources of nutrients for plants favors the recycling of nutrients and the maintenance of organic matter in the soil, improving its physical and chemical properties and favoring the maintenance of growth-promoting microorganisms. In addition, in conservationist organic coffee production systems, increasing soil organic matter makes it possible to sequester carbon from the atmosphere (Niguse et al., 2022).

Compared to conventional systems, in general, yields obtained in organic systems of coffee production are low, and producers depend on the premium obtained by organic certification for the activity to be economically viable. Therefore, the technical efficiency of these production systems needs to be increased (Siqueira et al., 2011; Carmo and Magalhães, 1999).

The efficient production of organic coffee presents several challenges, including selecting cultivars that are more adapted to this system of cultivation (Moura et al., 2014, 2017), and managing pests and diseases. The main problems, however, are nutritional in nature (Paulo et al., 2001, 2006; Moreira et al., 2014; Cardoso et al., 2018a).

As we know, extraction and export of nutrients from the soil are proportional to production. To maintain soil fertility and a sustainable production system over time, the nutrients exported by the harvest must be returned, especially in highly weathered soils with low CEC.

Organic sources of nutrients, such as coffee straw, residues from other crops, manure, animal litter, castor bean cake, ashes, bone, and blood meal, often do not have adequate concentrations or proportions of nutrients to meet the requirements of coffee trees. Moreover, few mineral sources of nutrients are admitted by organic certifiers and are limited to limestone, rock phosphates and thermo phosphates, and double sulfate of K and Mg.

Because N is the nutrient most required by coffee trees (Martinez et al., 2019), in general, the calculation of the doses necessary of an organic source of nutrients is based on its N concentration. As organic fertilizers generally have a low concentration of N, the doses of organic fertilizer required are usually very high, sometimes in the order of 20 t ha^{-1} (Ricci, 2005; Fernandes et al., 2013a, b). Another complicating factor is that other nutrients must be provided in sufficient quantities and proportions in addition to N.

Mixtures of different products to obtain adequate amounts and proportions of nutrients for the different stages of growth of the coffee plant would be an alternative, but obtaining such mixtures adds greater complexity to the production of the chosen organic fertilizer. Furthermore, previous mineralization of organic matter is necessary before the nutrients it contains are available for absorption by the roots. The decomposition rate of different materials varies according to a number of factors, including temperature, humidity, aeration and C/N ratio. Therefore, another bottle-neck and key to the success of organic coffee production is the synchrony between the release of nutrients from the organic source used and the demand of the plant, which can be challenging to obtain.

One possibility for supplying N to organic coffee production systems is the intercrop among coffee and N-fixing legumes (green manure). Additionally, in this case, the synchrony between the release of the N contained in the dry matter of the legume and the peak demand of the coffee plant continues to be the biggest challenge to be overcome. There are differences in both the N fixation capacity and the speed of decomposition of green manures (Barrela, 2010; Araujo, 2015; Cardoso et al., 2018b). Nevertheless, several studies on the climatic conditions in the Zona da Mata in Minas Gerais, Brazil, have shown that green manure could provide about 50 % of the required N (Cardoso et al., 2018a, b).

In summary, organic coffee production is a sustainable agronomic practice whose technical efficiency must be improved to ensure its competitiveness compared to other coffee production systems. Providing sufficient N for plant growth and production in its different phases is one of the bottlenecks to be overcome. Although more research in different climates and soil conditions is needed, good mixtures of different organic sources of nutrients, as well as intercropping between coffee and legumes, combined or not with other organic sources of N would be a viable alternative for increasing the supply of N and improving technical efficiency in organic coffee production systems.

Final Remarks

Most of the works mentioned above were published before the growing worry about the possible adverse effects of global warming on agriculture. For example, since the 1950s, organic coffee farming has been a subject of study. However, in these 70 years, new management practices have been adopted in coffee farming, and the use of new varieties and products (fertilizers and pesticides), which require a different or adapted agronomic view for each of these practices. The same applies to shading, considering that coffee originated in Ethiopian forests.

The achievement of sustainability and the improvement of a circular economy is an objective to be pursued by the coffee chain and all food production chains, to maintain food security and a healthy environment for humanity over the coming decades and centuries.

Our review has confirmed evidence that from the agronomic viewpoint, we already have techniques of production that can replace the traditional ones offering great advantages for the quality of the coffee orchard ecosystem, which translate into services and advantages for the entire ecosystem. The choice between different systems of coffee management will largely depend on the environmental factors to be mitigated, the market niche to be reached, and the particular socioeconomic conditions of each region or producer. In any situation, however, it is necessary to improve technical efficiency. Several gaps were evidenced. A quick refinement and improvement of sustainable agronomic techniques' efficiency depend on the amount of investment in scientific research in such areas.

On the other hand, as previously discussed, several sustainable management options could reduce productivity and farmers' income. As mentioned previously smallholders are responsible for about 70-80 % of coffee world production, and such production feeds a large chain of businesses comprising several participants with high financial movement and high profit.

Therefore, to achieve the sustainability desired, we need the engagement of the entire coffee chain, creating solutions that guarantee adequate profit to the beginning part of the chain, on which all subsequent steps are dependent.

In conclusion, sustainable practices may bring about several positive changes in coffee as a crop, starting with new sources of nutrients to complement chemical fertilizers and extending to social benefits to smallholder farmers and superior coffee quality for consumers.

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