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REVIEW

Pests and diseases regulation in coffee agroecosystems by management systems and resistance in changing climate conditions: a review

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Abstract
Coffea (Gentianales: Rubiaceae) is an economic plant considering its production income and the number of people that depend on it for their daily livelihoods. Tropical regions predicted to face severe challenges related to climate change impacts often grow coffee. Like other crops, coffee benefits from many ecosystem services, mainly regulating and supporting ecosystem services that play a role in production. Since the emergence of coffee pests and diseases, there have been two primary control techniques: pesticide application and crops management techniques. In most cases, chemical control is nearly ineffective and associated with pesticide resistance, environmental pollution, chemical hazards, and resurgence. This paper reviews management systems and coffee resistance. Studies show that management systems and plant resistance can maintain functional pest and disease regulatory ecosystem services within coffee plantations. We also evaluate how pest and disease regulation services can behave in climate change. The literature shows that managing coffee farms and plant resistance can mitigate the adverse effects of climate change on pest and disease regulation services. Therefore, they can maintain functional ecosystem services and help farmers in tropical areas adapt and be resilient to changing environmental conditions. It is crucial to update these ecological and environmentally friendly control techniques and understand how they will perform under future climate change. Based on the reviewed literature, we identify knowledge gaps and suggest three priority studies in this substantial area of future research. Finding solutions could enhance farmers' perception of interactions between regulation services and climate change and could support ensuring food security.

Keywords Biodiversity · Climate change · *Coffea arabica* L. · Ecosystem services · Natural enemies

Introduction

Coffea arabica, the species with an economic interest, is currently the source of foreign currency exchange in its production regions (Krishnan 2017). Millions of smallholder farmers depend heavily on coffee for their livelihoods, and an estimated 25 million farmers grow coffee on 11 million hectares (Jezeer et al. 2019). More than 15 million people in Ethiopia rely on coffee production (Ventocilla et al. 2020), whereas around 70% of foreign currency exchange in Rwanda comes from coffee exportation (Ngango and Kim 2019).

Coffee farming systems range from small traditional (in a conventional coffee farming system, coffee is cultivated simultaneously with other crops or agroforestry trees on the same land) to large modern systems (Arias et al. 2012). It varies with regions and land availability; that is why frequent systems in Tanzania, for instance, where farmers use low

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coffee tree densities favouring food crops, are different from those applied in Colombia (Bosselmann et al. 2009; Otieno et al. 2019). For example, in East Africa, coffee growers can face perpetual land fragmentations due to overpopulation (Rahn et al. 2018), resulting in more fragmented landscapes (Mosomtai et al. 2021), leading to multi-cropping coffee farming systems. In Uganda, coffee trees were grown along with food crops like bananas in rural areas (Rahn et al. 2018; Otieno et al. 2019) and also mixed with other agroforestry species (Mosomtai et al. 2020); that provide fodder for animals, medicinal, and fruits (Tumwebaze and Byakagaba 2016). Besides the shade and multi-cropping coffee management systems, coffee is also grown under other cropping systems such as coffee plantations, coffee forests, semi-forests, and gardens (Mitiku et al. 2018). However, coffee farmers shift from original shaded cultivation practices towards shade-free productions based on a debate assumption that shade lowers yields and increases pests and diseases in coffee plants (Jimenez-Soto 2020).

Coffee producers face challenges related to price fluctuation, climate change, arthropod pests and diseases (Hindorf and Omondi 2011; Carvalho et al. 2019). The significant diseases are the coffee berry disease (*Colletotrichum Kahawae*), the coffee leaf rust (*Hemileia vastatrix*), and the coffee wilt diseases (*Gibberella xylarioides* (*Fusarium xylarioides*) (Hindorf and Omondi 2011). The significant pests are the coffee berry borer *Hypothenemus hampei* Ferrari (Coleoptera: Curculionidae); the coffee leaf miner *Leucoptera coffeella* Guérin (Lepidoptera: Lyonetiidae), the antestia bug *Antestiopsis orbitalis* Westwood (Hemiptera: Pentatomidae), and the scale insects *Coccus viridis* Green and *Coccus celatus* Green (Hemiptera: Coccidae) (Nair 2021). Farmers apply different techniques in managing coffee pests and diseases depending on the available human and financial resources and the degree of infestations. These techniques include using tolerant varieties, biological control by conservation, crop management, pesticides application, and the mass trapping technique (Attractant-baited traps), especially to control the coffee berry borer *H. hampei* (Fernandes et al. 2015; Vega et al. 2015b).

Coffee growers reduce pest incidences and severity in coffee by managing agroecological systems (Altieri and Nicholls 2020). In those systems, several mechanisms may intervene in pests and diseases management; they involve (a) pest deterrence or repellence (Ratnadass et al. 2012), (b) pest stimulation or attraction, (c) push–pull[1] strategy, (d) trap crops[2] (Peterson et al. 2016), (c) stimulation of soil pest pathogens antagonists, (d) refuge or shelter for natural enemies, (e) alternative source of food for natural enemies, (g) physical barrier effects, (h) diversification of natural enemies, (i) unfavourable microclimate and (j) improvement of soil fertility that enhance the vigour of the plant (Knolhoff and Heckel 2014; Kumar 2016).

Still, with coffee intensifications, the multi-cropping is shifting to mono-cropping systems, resulting in biodiversity losses. Modern coffee farming systems enhance agrochemicals (inorganic fertilizers and pesticides), including endosulfan, chlorpyriphos, and copper sulphate sprayed to manage coffee pests (Chain-Guadarrama et al. 2019). For instance, farmers apply insecticides far more frequently in Rwanda than any recommended pest control measures (Harelimana 2018). In the same country, Governments use and recommend pesticides in coffee trees and food crops (Clay 2018). In that area, poor rural communities that cannot afford pesticide prices acquire pesticides from governments as credit paid back by deducting the cost of the coffee selling price after harvesting (Ortega et al. 2019).

Most pesticides are toxic to human beings and the environment, and there is evidence that coffee pests develop resistance to these high eco-toxic pesticides (Chain-Guadarrama et al. 2019). For instance, in Tanzania, coffee farmers in this country suffer from chemical hazards because of the frequent application of pesticides (Ngowi et al. 2001). In contrast, residues of endosulfan have been found in marine biota in different geographical regions of the Arctic (Weber et al. 2010).

Thus, awareness about the negative consequences of pesticide application may lead to using more environmentally and health-friendly methods to rescue and retrieve regulating ecosystem services and enhance the management of natural resources.

Pests and diseases have been kept under an economic injury level by using less susceptible varieties. The most dramatic early success in plant resistance was the control of grape phylloxera *Daktulosphaira vitifolia* Fitch (Hemiptera: Phylloxeridae) in European grapevines around 1890 by grafting susceptible scions of *Vitis vinifera* L. on resistant rootstocks *Vitis labrusca* L. (Metcalf and Luckmann 1994). Plants respond to the attack of pests, and this has forced plants to develop various defence strategies, but the selective pressure and co-evolution led insects to develop strategies to detoxify plant chemicals in their food (Simms and Fritz 1990). For example, the coffee berry borer *H. hampei* has evolved an adaptation to handle the toxic effects of caffeine

[1] Push–pull strategy was developed in Kenya as an alternative method to manage both pest and weed; it uses a combination of intercropped repellent plants to deter the stem borers from the maize (pull) and trap crops to attract repelled pest (Lenné and Wood 2011).

[2] Trap crops or trap plants emit signals and attract a pest that feeds on it. However, the hosts have negative effects on pest fecundity, survivorship and result to a pest death.

(Guerreiro Filho and Mazzafera 2003). Thus, there is a need for a continuous breeding program for resistance to pests and diseases to get plants that can evolve with pathogens that overcomes the resistance of coffee.

Multi-cropping coffee management approaches can also improve the livelihoods of rural communities as they facilitate the adaptation of coffee production to climate change (Gomes et al. 2020). By the definition of climate change, parameters are the rise of global temperature, the elevation of carbon dioxide concentration in the atmosphere, erratic rainfall, and a change in radiation (Choudhury and Saha 2021). Climate change can impact coffee cultivation by decreasing climatic suitability at lower altitudes and higher latitudes, affecting flowering and fruiting stages, and increasing pressure from pests and disease (Chain-Guadarrama et al. 2019). It is crucial to raise awareness of changing environmental conditions and bring attention to researchers, farmers and decision-makers on how pests and pathogens pressure will become under future climate change.

This review paper focuses on synthesized findings on pests and diseases regulation by coffee management systems and plant resistance. It identifies skills gaps and suggests priority studies for possible sustainable solutions. Specifically, this article pays attention to coffee management systems and coffee resistance, promising and sustainable methods to rescue ecosystem services and mitigate climate change effects on coffee yields.

Coffee management systems

Coffee management systems can play a significant role in crop productivity (Bongers et al. 2015). The management systems include shading trees, pruning and de-sucking, intercropping with leguminous crops, soil fertility management and weeding. Even if enhancing these management practices requires financial means, they have shown to significantly increase productivity directly and increase revue through coffee value addition at the farm level (Bongers et al. 2015) and regulate coffee pests and diseases (Avelino et al. 2012).

Increase coffee productivity through management systems

The coffee management system, especially the multi-cropping system, is practised by farmers to diversify the source of food and revenues. Moreover, coffee management systems can contribute a lot to diversifying biological diversities and can promote its quality and food security. For example, the productivity of coffee (arabica species) in Uganda was of good quality, and its volume increased due to coffee shaded with banana crops (Van Asten et al. 2012). A shade may positively influence coffee berries production by creating a microclimate production of mulch materials that improve soil fertility and moisture (Van Asten et al. 2012). The preservation of natural landscapes, especially its connectivity to the plantation of coffee trees that promotes pollination, can increase productivity by up to 32% (Latini et al. 2020). For instance, in Northern of Kilimanjaro in Tanzania, the quality and fruit weight decrease by 7.4% when farmers exclude pollinator agents from coffee flowers (Classen et al. 2014). A study conducted in Toba Highlands (North Sumatra) indicated that Pruning of coffee trees is the first step to increasing coffee productivity and helps to reduce the infestation of coffee berry borers (Dufour et al. 2019). The intercropping with plant species that can fix atmospheric nitrogen, like Inga plants in Brazil, significantly contributes to the weight of coffee fruits (Rezende et al. 2021) and indirectly increases the revenues. Moreover, crop management, like weeding, can enhance the development of mycorrhizal fungi, reduce the infestation of nematodes, and improve productivity and ecosystem services sustainability (Arias et al. 2012; Mahdhi et al. 2017). Comparing all management systems in terms of increasing coffee production is crucial. It can help farmers know and rank from the most to the least promising management system, as the present work cannot rely on the literature review to indicate which approach should be promoted.

Pests and diseases regulation in coffee agro-ecosystems

Coffee always benefits from various ecosystem services. Coffee gives more yield, good quality, and biodiversity enhancement when grown under shade or polyculture systems (Tscharntke et al. 2011). In combination with reducing the pesticides in coffee trees, these systems can protect functional agrobiodiversity such as antagonists of pests, pollinating insects (regulating ecosystem services) and consequently enhance coffee yields (Tscharntke et al. 2011). Shaded coffee trees and an adequately managed vegetation structure can offer many ecological niches. They have improved the abundance of native natural enemies (Pak et al. 2015) and entomopathogenic fungi that control coffee pests (Mariño et al. 2016). For example, in Brasil, shaded coffee systems increase the rate of parasitism and predation of coffee leaf miners (Rosado et al. 2021) by augmenting potential pest control agents like lizards (Sinu et al. 2021). These cropping systems can provide refuge or shelter for natural enemies and can be alternative food sources for natural enemies. In American Neotropics, increasing the habitat quality of land used for coffee production by favouring shade trees that support important insects in bird diets can impact bird conservation, controlling coffee pests (Narango et al. 2019). Even if shade trees may increase the severity and incidence of coffee foliar diseases in Nicaragua, they can decrease the disease prevalence through soil fertility improved through higher soil litter cover (Teixeira et al. 2021), indirectly can increase yields (Durand-Bessart et al. 2020). A shade can reduce diseases through direct regulations, act as the reservoir of natural enemies, and create unfavourable pathogen development conditions (Ratnadass et al. 2012). Gathering the information on the provision of ecosystem services by coffee management systems can be worthwhile to optimize and sustain biological diversity benefits.

The coffee berry borer (*H. hampei*)

H. hampei is a species of the order Coleoptera that feeds on the fruits of coffee. This pest is the prey of birds, bats, and other living organisms found in the coffee agroecosystems. Insectivorous birds and bats are abundant in traditional coffee management systems in Costa Rica, Colombia and successfully regulate coffee pests, particularly *H. hampei* and white stem borers (Karp et al. 2013; Escobar-Ramírez et al. 2019). The exclusion of these systems favouring modern systems can lead to the resurgence of pests and diseases in the coffee agroecosystems that growers encounter these days. For instance, birds exclusion from foraging on coffee shrubs doubles coffee berry borer populations in Costa Rica (Karp et al. 2013). In Mexico, immature coffee berry borers are removed from the infested berries by ants in diversified coffee management systems (Morris and Perfecto 2016; Bagny Beilhe et al. 2020). In traditional coffee management systems in Mexico, Nicaragua, El Salvador, Guatemala, Peru, Indonesia, and Costa Rica, spiders are abundant and active; they can consume more than 40 million insect pests per hectare per year; (Jha et al. 2014).

These traditional coffee management systems can act differently, although they end with pests controlled. In addition to enhancing the population of native predators and parasitoids, traditional coffee management systems can create a micro-climate that is unfavourable to the development of the coffee berry borer (Mariño et al. 2016); and indirectly increase the population of nematodes that feed on *H. hampei* (Escobar-Ramírez et al. 2019). Moreover, coffee management by multi-cropping systems with repellent species in Colombia (for example, *Lantana camara* and *Nicotiana tabacum)* and pruning of trees in Hawaii and Puerto Rico (Aristizábal et al. 2017) reduce the infestation of coffee berry borer by releasing volatile compounds sesquiterpenes (Castro et al. 2017). Coffee intercropped with agroforestry, shaded coffee, multi-cropping systems, and small forestry patches on farm edges can support pest regulation services in coffee trees (Chain-Guadarrama et al. 2019; Bagny Beilhe et al. 2020; Rosado et al. 2021). The sustainability of these traditional practices may require the efforts of decision-makers on one side and incentives on the side of coffee farmers. These scientific studies suggest that eliminating a shade cover or polycultures in coffee trees and considering changing environmental conditions can ultimately result in increased coffee berry borer problems.

The coffee leaf miner (*Leucoptera coffeella)*

Farmers use the contact and systemic insecticides, although systemic insecticides are preferred. The literature reveals that in Brasil, insecticides are ineffective as this pest has shown the capacity to resist Thiamethoxam and Chlorantraniliprole (Leite et al. 2021). Therefore, there is a need to promote existing approaches to control leaf miners without harming the environment. For instance, in Brasil, intercropping coffee with rubber trees acts as a shelter and reduces the air circulation within trees, which changes into unfavourable conditions for the development of leaf miners (Androcioli et al. 2018).

Moreover, shaded coffee systems in Puerto Rico may control this pest by increasing twig-nesting ants, which feed on eggs, larva, pupa and affect oviposition (Mora et al. 2008; Vandermeer et al. 2010) and by increasing the population of predators, especially lizards (Perfecto et al. 2021). The few existing studies on the management of coffee leaf miners by management systems indicate that environmental conditions might influence this pest more than other living organisms. We hypothesize that if climate shifts to favourable climate conditions due to the removal of traditional coffee farming systems in favour of intensification, the population of leaf miners can increase and affect the production of coffee. Gathering information on life-history traits is crucial and can help predict population variations of leaf miners over time and under a changing climate.

Coffee scales insects (coccus spp), mealybugs (*Planococcus* spp), and *Toxoptera aurantii*

Coffee sucking pests are found in young plantations and on smooth (buds) parts (Harelimana 2018) and a high concentration of Carbon dioxide influences the infestation of sucking insects (Kremer et al. 2018). For example, under a high concentration of Carbon dioxide, a plant host grows faster, increases sucrose, and enhances sucking insects to produce more honeydew (Blanchard et al. 2019) which can attract more ants that interfere with parasitism (Fanani et al. 2020). Traditional coffee farming systems like multi-cropping and shaded trees can solve these challenges by creating micro-climate (Ennis and Philpott 2019) and Carbon sequestration (Zaro et al. 2020). Apart from the shade in coffee that provides a better yield of good quality than unshaded coffee (Muschler 2001), the shaded coffee system reduces the infestation of scales and mealybugs in Uganda (Karungi et al. 2015). The relative lower sucking insects pest levels in shaded coffee production systems are attributed to complex insect communities and food webs that result in high species diversity in such systems (Bianchi et al. 2006). The high biodiversity coupled with watershed services may also reduce pest incidences and damages in shaded coffee polycultures (Dossa et al. 2008).

The infestation of coffee aphids in Rwanda is reduced in coffee intercropped with *Phaseolus Vulgaris* L. (Harelimana 2018). However, they are more abundant in treated coffee with insecticide than in untreated coffee plantations in Tanzania. This can clearly explain the harmful effects of pesticides on regulating ecosystem services.

The coffee berry disease (*Colletotrichum Kahawae)*

The increased intensity of the coffee berry disease (CBD) is strongly associated with reduced disease management practices and production systems in Ethiopia, where this disease is on an upsurge (Alemu et al. 2016). Researchers have identified agro-cultural practices that are likely to reduce losses in Cameroon where the maintenance pruning and multi-cropping with shade plants can limit the coffee berry borer development (Mouen Bedimo et al. 2007). The variation of isolates of CBD must be considered in developing cultivars resistant to CBD (Alemu et al. 2021). In Kiambu County, growing coffee trees under shade can reduce the development and the spread of coffee berry diseases (Kebati et al. 2016).

The coffee leaf rust *(Hemileia vastatrix)*

Shade trees can provide pest and diseases regulation services by enhancing microclimate (Avelino et al. 2004), providing refuges for pest and disease antagonists (Avelino et al. 2018). By increasing throughfall and reducing raindrop kinetic energy below the shade, coffee trees seem crucial to improved Coffee leaf rust regulation (Avelino et al. 2020). Shades through reduced fruit load can control the fungi *H. vastatrix* (López-Bravo et al. 2012).

Coffee resistance

Some chemical groups such as alkaloids and caffeoylquinic acids are present in the flowers, leaves, seeds, green, and roasted coffee; they act as insecticides (Green et al. 2015). In a broader context, caffeine repels insects that would not normally encounter it in their host plants when introduced into a plant (Green et al. 2015). Breeding and multiplication of new varieties adapted to the changing conditions of pests, disease, and climate are worthwhile (van der Vossen et al. 2015). Despite its importance and environmentally friendly technique, few publications on coffee resistance to its pests exist.

The coffee berry borer (*Hypothenemus hampei)*

The literature shows that *H. hampei* is likely to resist insecticides; it also indicates that the promotion of coffee resistance can be effective when regularly monitored. The presence of trypsin and chymotrypsin in the diet of coffee pests like *H. hampei* retards growth and development, ultimately causing death (Damon 2000). The resistance of different coffee genotypes to the coffee berry borer *H. hampei,* under both natural and controlled environmental conditions, has been evaluated. The high polyphenol-oxidase (PPO) activity in young leaves and fruit endosperm has been related to defence mechanisms against coffee insects (Mazzafera and Robinson 2000). Still, the coffee tree resistance may be related to the oxidative potential of the tissue regarding the phenolic composition rather than simply to a higher PPO activity (Melo et al. 2006). The concerned genotypes *Coffea eugenioides*, *C. kapakata,* and *Psilanthus bengalensis* Roxb and Schult (Rubiaceae) showed resistance to coffee berry borer, and they have essential resistance traits to incorporate in other coffee genotypes (Sera et al. 2010). The analysis of a genome of *H. hampei* revealed the presence of enzymes able to detoxify and digest toxic compounds of coffee, including caffeine which is the most preferred product for coffee consumers (Vega et al. 2015a). The breeding for the resistance of coffee to *H. hampei* must consider the variation of endosymbionts, enzymes fluctuation and under changing environment. Furthermore, it is crucial to evaluate the chemical composition of coffee berries and their durability under a shade cover, a climate change compared to berries produced from sun-exposed plantations. This study can predict the required time for borers in changing environmental conditions to overcome the resistance.

The coffee leaf miner (*Leucoptera coffeella*)

The transfer of resistant genes from *C. racemosa* to the highly productive and susceptible varieties of *C. arabica* is crucial in developing resistant varieties (Leroy et al. 2000). However, genetically modified coffee is a limitation to markets (Ribas et al. 2006). The well-known and successful case in coffee plants is using resistant genes by crossing *Coffea racemosa* L. to *C. arabica,* which generated a resistant hybrid to the coffee leaf miner (Guerreiro Filho 2006). Because insects can evolve with the resistance of plants, there is a need to evaluate the sustainability of these varieties in changing environmental conditions

Table 1 Synthesis of reviewed coffee pests' regulation by agroecological management systems

Coffee management systems	Controlled pests	Regions	References
Shaded coffee management systems	*H. hampei*	South America: Puerto Rico, Colombia East Africa: Kenya	(Mariño et al. 2016; Milligan et al. 2016; Atallah et al. 2018)
Keeping forests patches in surrounding coffee landscapes		South America (Brasil)	(Aristizábal and Metzger 2019; Escobar-Ramírez et al. 2019)
Coffee consorted with inga (*Inga edulis*) trees		South America: Brasil	(Rezende et al. 2021)
Intercropping coffee with repellent species (*Lantana camara*, *Nicotiana tabacum)*		South America (Colombia)	(Castro et al. 2017)
Intercropping coffee with rubber trees	*Leucoptera coffeella*	South America (Brasil)	(Righi et al. 2013; Androcioli et al. 2018)
Shaded-coffee farming systems		South America (Mexico)	(Mora et al. 2008; Vandermeer et al. 2010)
		South America (Puerto Rico	(Perfecto et al. 2021)
Intercropping of coffee with various species like pigeon pea		South America	(Amaral et al. 2010)
Coffee consorted with inga (*Inga edulis*) trees		South America: Brasil	(Rezende et al. 2021)
Sun coffee farming system (Sun plantation)		South America (Puerto Rico)	(Borkhataria et al. 2012; Azrag et al. 2017)
Shaded coffee polycultures	*Antestiopsis thunbergii*	West Africa	(Philpott and Armbrecht 2006)
	Planococcus spp	East Africa: Uganda	(Karungi et al. 2015) (Vandermeer et al. 2010)
	Toxoptera aurantii	East Africa: Uganda	(Karungi et al. 2015)
Coffee intercropped with a high density of pawpaw (*Carica papaya*)	*Xylosandrus compactus* (Coleoptera: scolytidae)	East Africa (Luweero region): Uganda	(Bukomeko et al. 2018)

and evaluate their productivity and capability to keep the resistance over time (Table 1).

Host resistance overpassed

Coffee is primarily a chemical defended plant because its leaves contain high alkaloids concentrations, but the coffee leaf miner is overcoming the resistance of coffee (Guerreiro Filho and Mazzafera 2000). For example, the coffee berry borer *H. hampei* has evolved to handle the toxic effects of caffeine (Guerreiro Filho and Mazzafera 2003), whereas the coffee leaf rust is overpassing the resistant varieties partially (Alemu et al. 2016). Thus, there is a need for a continuous breeding program to obtain plants that can evolve with a pest to break biotypes that possess an inherent genetic capability to overcome the resistance of coffee.

Indirect interaction between coffee resistance and natural enemies

In a natural environment, organisms interact to survive. This interaction can be among individuals of the same species or different species. For example, coffee trees infested by the coffee berry borer *H. hampei* attracted its parasitoids *Prorops nasuta* Waterston (Hymenoptera: Bethylidae) (Chiu-Alvarado et al. 2009) which reduced coffee berry borer populations. There are few studies on the effects of plant resistance to natural enemies of pests. Studies show that the resistance interferes with pest biology and affects the efficiency of natural enemies (Michereff et al. 2015). For example, caffeine, a major alkaloid found in coffee, is transmitted in a trophic chain; it indirectly affects the development and longevity of parasitoids (Tougeron and Hance 2021). The breeding for coffee resistance can consider the effect of resistant varieties on the survival, fecundity and fitness of natural enemies, particularly the parasitoids and predators (Fig. 1).

Effects of climate change on pest and disease regulations in coffee agroecosystems

The literature associated climate change with increased CO_2 (carbon dioxide) levels, higher seasonal temperature profiles, and precipitation. These global climate change effects will affect the distribution of pests (Lamichhane et al. 2015). The literature indicates that the temperature likely drives the

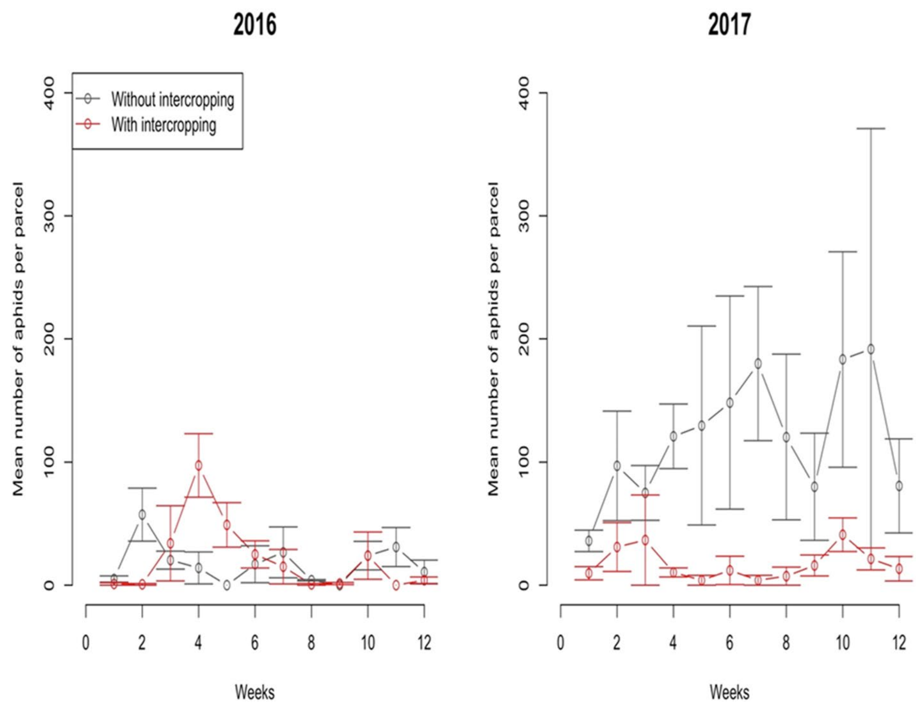

Fig. 1 Variation of aphid populations (Mean ± SE) in coffee with and without intercropping for 2016 and 2017 (Harelimana Anastase 2018)

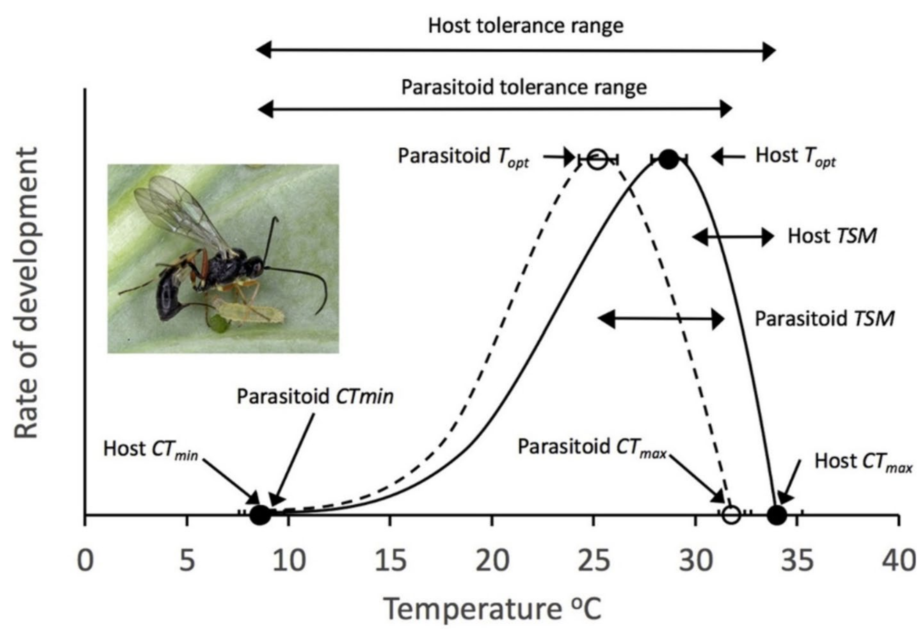

Fig. 2 The rate of the development of a host and parasitoid under changing temperatures. *Source* (Furlong and Zalucki 2017)*, we sought authorization to reproduce this figure from the Author: Professor Mike Furlong, School of Biological Sciences, The University of Queensland, Brisbane QLD 4072 Australia, m.furlong@up.edu.au*

development time, longevity, reproduction, and phenology; these biological parameters change with different climatic conditions. However, some pests can adapt to changing environmental conditions; this is the case of *H. hampei* whose population increases under higher temperatures. Furthermore, increasing temperature affects the interaction between the host and natural enemies (Fig. 2) (Furlong and Zalucki 2017). It indicates that the high temperature may lead to the exclusion of parasitoids in areas where they are needed.

Upon modelling reproduction with temperature, studies also concluded that East African coffee regions would see a doubling of the number of generations of *H. hampei* as temperatures increase with climate change (Rice 2018). Besides the temperatures, the elevated concentration of carbon dioxide positively influences the population growth rate of insects (Guo et al. 2013). A few studies considered the potential impacts of climate change on coffee pests and diseases (Verburg et al. 2019). We tried to review and summarize the few documents reported on coffee pests. These studies reveal that when the temperature is high, the area can become suitable for the African coffee white stem borer, *Monochamus leuconotus* (Kutywayo et al. 2013), while the predation of coffee leaf miners becomes low (Lomelí-Flores et al. 2010). It is likely the same for the coffee berry borer *H. hampei*; the increase in temperature leads to the rise of coffee berry borer infestations and a reduction of the *Coffee arabica* protection (Jaramillo et al. 2011; Jonsson et al. 2015). The reviewed literature indicates that shaded and multi-cropping coffee systems are promising pest management approaches to mitigate climate change effects on insects; decision-makers need to document and sustain these ecological pest management approaches.

Biological factors

The environmental fluctuations force an insect to adapt to the changing conditions through phenotypic plasticity and indirectly change the interactions with other species. Cold and extreme temperatures change the developmental period, lifespan, fecundity, sex ratio, activity, and distribution, of pests and natural enemies (Hance et al. 2007). Short term-temperature fluctuations can cause substantial stress on pest species and their antagonists, substantially influencing their interactions (Coll and Wajnberg 2017). Climate may influence plant architecture and biomass, chemical defence, and nutritional value, each of which may, in turn, affect how animals use the habitat (Schmitz and Barton 2014). Predicting how plant species will be in terms of nutritional value, health, the time needed to complete their life cycle, and other living organisms' response to changing environmental conditions is a big concern. At the same time, it is the centre of gathering information and mitigating adverse effects on trophic chains and ecological interactions.

Pesticides

Pesticides are the most used technique to manage pests on their farms. Due to the increase in temperatures, pests outbreaks will occur, and indirectly, farmers will apply the pesticides at a high level. The misuse of pesticides will result in cross-tolerance to temperature (Coll and Wajnberg 2017) to pest's resurgence and the loss of biodiversity and consequently limiting regulation ecosystem services.

Semiochemicals

Semiochemicals, organic molecules involved in chemical interactions among organisms, are the basis of insects communication (Boullis et al. 2016). The communication is between individuals of the same species (they use pheromones) or individuals of different species (allelochemicals). Pheromones play roles in insect sexual behaviour, foraging, and aggregation (Wyatt 2014). The sustainability of a pest regulation ecosystem service will rely on gathering information on changing and variations of semiochemicals under changing environmental conditions. It will help predict the effect of climate change on integrated pest management and coffee pest autoregulation. Warmer rearing conditions led to higher relative amounts of compounds with high molecular weight.

Consequently, a shift in temperature could weaken intraspecific relationships of these insect species by reducing the efficiency; of their chemical communication. Moreover, changes in CO2 concentrations affect plant biochemistry, including the synthesis of secondary metabolites phytophagous insects produce their pheromones based on precursors taken from host plants. They could be among the most vulnerable arthropods to changes in atmospheric CO2 concentrations through cascade effects of CO2 on plant chemistry (Boullis et al. 2016).

Knowledge gaps and perspectives

This article reviews research on coffee management systems and coffee resistance. They represent an opportunity for pests and disease control by supporting and regulating ecosystem services. In addition, the paper also focuses on how services will be under changing environmental conditions. This area is very substantial for future research. Empirical studies reveal that management systems and coffee resistance provide regulating and supporting services that improve coffee productivity and quality and indirectly increase revenues. The gaps in this area have not been exhausted; we identify critical priorities for future research.

- The information on the effects of coffee farming management systems on the diversity and abundance of natural enemies and pathogen antagonists of soil and aerial pests is lacking. Thus, there is a need to quantify the impact of most coffee management systems practised around the World on the diversity of natural enemies of insects and disease antagonists in the soil. *Can coffee management systems affect both underground and aerial pests and disease antagonists at the same level?*
- We also notice that smallholder farmers are shifting from traditional coffee management systems to coffee intensification, thinking that conventional methods reduce coffee yields. Therefore, gathering more information on incentives to smallholder farmers and spatial cost–benefit analysis of coffee under shade or multi-cropping scenarios in coffee trees is uncomparable. Finally, there is a need to deeply analyse the cost–benefit, ecological benefits, sustainability, and adaptability to climate change. The analy-

sis may provide a clear return on investment for coffee management systems to encourage farmers to enhance, promote, and rescue ecosystem services, emphasizing pest and disease regulation services destroyed by modern coffee farming systems. *How can farmers optimize the production factors (land, agricultural practices, capital, technology, labour) under multi-cropping scenarios?*
- The literature reveals that coffee plants can lose the capacity to resist plant pathogens, and climate change is one of the factors contributing to the resurgence of new biotypes and strains. Breeding for coffee trees to adapt to climate change, pests and diseases' plasticity under changing environmental conditions is lacking. A good crop variety can be the one that is resistant to new strains or biotypes of emerging pests and diseases and which yields good quality and quantity under climate change conditions. *Are predators and parasitoids of coffee pests developing phenotypic plasticity to adapt to climate change conditions?*

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Declarations

Conflict of interest We have no conflicts of interest to disclose.

References

Alemu K, Adugna G, Lemessa F, Muleta D (2016) Current status of coffee berry disease (Colletotrichum kahawae Waller and Bridge) in Ethiopia. Arch Phytopathol Plant Prot 49:421–433

Alemu K, Adugna G, Lemessa F, Muleta D (2021) Pathogenic variability among Colletotrichum kahawae Waller and Bridge population from major coffee growing regions of Ethiopia. Indian Phytopathol 74:919–928

Altieri MA, Nicholls CI (2020) Agroecology: challenges and opportunities for farming in the Anthropocene. Cienc e Investig Agraria: Rev Latinoam De Cienc De La Agric 47:204–215

Amaral DS, Venzon M, Pallini A, Lima PC, DeSouza O (2010) A diversificação da vegetação reduz o ataque do bicho-mineiro-do-cafeeiro Leucoptera coffeella (Guérin-mèneville) (Lepidoptera: Lyonetiidae)? Neotrop Entomol 39:543–548

Androcioli HG, Hoshino AT, de Menezes Júnior AO, Morais H, Bianco R, Caramori PH (2018) Coffee leaf miner incidence and its predation by wasp in coffee intercropped with rubber trees. Coffee Sci 13(3):389

Arias RM, Heredia-Abarca G, Sosa VJ, Fuentes-Ramírez LE (2012) Diversity and abundance of arbuscular mycorrhizal fungi spores under different coffee production systems and in a tropical montane cloud forest patch in Veracruz, Mexico. Agrofor Syst 85:179–193

Aristizábal LF, Johnson M, Shriner S, Hollingsworth R, Manoukis NC, Myers R, Bayman P, Arthurs SP (2017) Integrated pest management of coffee berry borer in Hawaii and Puerto Rico: current status and prospects. Insects 8:123

Aristizábal N, Metzger JP (2019) Landscape structure regulates pest control provided by ants in sun coffee farms. J Appl Ecol 56:21–30

Atallah SS, Gómez MI, Jaramillo J (2018) A bioeconomic model of ecosystem services provision: coffee berry borer and shade-grown coffee in Colombia. Ecol Econ 144:129–138

Avelino J, Allinne C, Cerda R, Willocquet L, Savary S (2018) Multiple-disease system in coffee: from crop loss assessment to sustainable management. Annu Rev Phytopathol 56:611–635

Avelino J, ten Hoopen GM, DeClerck FA (2012) Ecological mechanisms for pest and disease control in coffee and cacao agroecosystems of the Neotropics. Ecosystem services from agriculture and agroforestry. Routledge, pp 125–152

Avelino J, Vílchez S, Segura-Escobar MB, Brenes-Loaiza MA, de Virginio Filho EM, Casanoves F (2020) Shade tree Chloroleucon eurycyclum promotes coffee leaf rust by reducing uredospore wash-off by rain. Crop Prot 129:105038

Avelino J, Willocquet L, Savary S (2004) Effects of crop management patterns on coffee rust epidemics. Plant Pathol 53:541–547

Azrag AGA, Murungi LK, Tonnang HEZ, Mwenda D, Babin R (2017) Temperature-dependent models of development and survival of an insect pest of African tropical highlands, the coffee antestia bug Antestiopsis thunbergii (Hemiptera: Pentatomidae). J Therm Biol 70:27–36

Bagny Beilhe L, Roudine S, Quintero Perez JA, Allinne C, Daout D, Mauxion R, Carval D (2020) Pest-regulating networks of the coffee berry borer (Hypothenemus hampei) in agroforestry systems. Crop Prot 131:105036

Bianchi FJ, Booij CJH, Tscharntke T (2006) Sustainable pest regulation in agricultural landscapes: a review on landscape composition, biodiversity and natural pest control. Proc R Soc b: Biol Sci 273:1715–1727

Blanchard S, Lognay G, Verheggen F, Detrain C (2019) Today and tomorrow: impact of climate change on aphid biology and potential consequences on their mutualism with ants. Physiol Entomol 44:77–86

Bongers G, Fleskens L, Van de Ven G, Mukasa D, Giller KEN, Van Asten P (2015) Diversity in smallholder farms growing coffee and their use of recommended coffee management practices in Uganda. Exp Agric 51:594–614

Borkhataria RR, Collazo JA, Groom MJ (2012) Species abundance and potential biological control services in shade vs. sun coffee in Puerto Rico. Agr Ecosyst Environ 151:1–5

Bosselmann AS, Dons K, Oberthur T, Olsen CS, Ræbild A, Usma H (2009) The influence of shade trees on coffee quality in smallholder coffee agroforestry systems in Southern Colombia. Agr Ecosyst Environ 129:253–260

Bukomeko H, Jassogne L, Kagezi GH, Mukasa D, Vaast P (2018) Influence of shaded systems on Xylosandrus compactus infestation in Robusta coffee along a rainfall gradient in Uganda. Agric for Entomol 20:327–333

Carvalho CF, Carvalho SM, Souza B (2019) Coffee. In: Souza B, Vázquez LL, Marucci RC (eds) Natural enemies of insect pests in neotropical agroecosystems: biological control and functional biodiversity. Springer International Publishing, Cham, pp 277–291

Castro AM, Tapias J, Ortiz A, Benavides P, Góngora CE (2017) Identification of attractant and repellent plants to coffee berry borer, Hypothenemus hampei. Entomol Exp Appl 164:120–130

Chain-Guadarrama A, Martínez-Salinas A, Aristizábal N, Ricketts TH (2019) Ecosystem services by birds and bees to coffee in a changing climate: a review of coffee berry borer control and pollination. Agr Ecosyst Environ 280:53–67

Chiu-Alvarado P, Barrera JF, Rojas JC (2009) Attraction of prorops nasuta (Hymenoptera: Bethylidae), a parasitoid of the coffee berry borer (Coleoptera: Curculionidae), to host-associated olfactory cues. Ann Entomol Soc Am 102:166–171

Choudhury PP, Saha S (2021) Dynamics of pesticides under changing climatic scenario. Environ Monit Assess 192:814

Classen A, Peters MK, Ferger SW, Helbig-Bonitz M, Schmack JM, Maassen G, Schleuning M, Kalko EK, Böhning-Gaese K, Steffan-Dewenter I (2014) Complementary ecosystem services provided by pest predators and pollinators increase the quantity and quality of coffee yields. Proc R Soc b: Biol Sci 281:20133148

Clay N (2018) Seeking justice in green revolutions: synergies and trade-offs between large-scale and smallholder agricultural intensification in Rwanda. Geoforum 97:352–362

Coll M, Wajnberg E (2017) Environmental pest management: challenges for agronomists, ecologists economists and policymakers. John Wiley & Sons, Chichester

Damon A (2000) A review of the biology and control of the coffee berry borer, Hypothenemus hampei (Coleoptera: Scolytidae). Bull Entomol Res 90:453–465

Dossa EL, Fernandes ECM, Reid WS, Ezui K (2008) Above-and belowground biomass, nutrient and carbon stocks contrasting an open-grown and a shaded coffee plantation. Agrofor Syst 72:103–115

Dufour BP, Kerana IW, Ribeyre F (2019) Effect of coffee tree pruning on berry production and coffee berry borer infestation in the Toba Highlands (North Sumatra). Crop Prot 122:151–158

Durand-Bessart C, Tixier P, Quinteros A, Andreotti F, Rapidel B, Tauvel C, Allinne C (2020) Analysis of interactions amongst shade trees, coffee foliar diseases and coffee yield in multistrata agroforestry systems. Crop Prot 133:105137

Escobar-Ramírez S, Grass I, Armbrecht I, Tscharntke T (2019) Biological control of the coffee berry borer: main natural enemies, control success, and landscape influence. Biol Control 136:103992

Fanani MZ, Rauf A, Maryana N, Nurmansyah A, Hindayana D (2020) Parasitism disruption by ants of Anagyrus lopezi (Hymenoptera Encyrtidae), parasitoid of cassava mealybug. Biodivers J Biol Divers. https://doi.org/10.13057/biodiv/d210601

Fernandes FL, Picanço MC, Fernandes MES, Dângelo RAC, Souza FF, Guedes RNC (2015) A new and highly effective sampling plan using attractant-baited traps for the coffee berry borer (Hypothenemus hampei). J Pest Sci 88:289–299

Furlong MJ, Zalucki MP (2017) Climate change and biological control: the consequences of increasing temperatures on host–parasitoid interactions. Curr Opin Insect Sci 20:39–44

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

Green PWC, Davis AP, Cossé AA, Vega FE (2015) Can coffee chemical compounds and insecticidal plants be harnessed for control of major coffee pests? J Agric Food Chem 63:9427–9434

Guerreiro Filho O (2006) Coffee leaf miner resistance. Braz J Plant Physiol 18:109–117

Guerreiro Filho O, Mazzafera P (2000) Caffeine does not protect coffee against the leaf miner Perileucoptera coffeella. J Chem Ecol 26:1447–1464

Guerreiro Filho O, Mazzafera P (2003) Caffeine and resistance of coffee to the berry borer Hypothenemus hampei (Coleoptera: Scolytidae). J Agric Food Chem 51:6987–6991

Guo H, Sun Y, Li Y, Tong B, Harris M, Zhu-Salzman K, Ge F (2013) Pea aphid promotes amino acid metabolism both in Medicago truncatula and bacteriocytes to favor aphid population growth under elevated CO2. Glob Change Biol 19:3210–3223

Hance T, van Baaren J, Vernon P, Boivin G (2007) Impact of extreme temperature on parasitoids in a climate change perspective. Annu Rev Entomol 52:107–126

Harelimana A (2018) Consequences of varietal resistance of Coffea arabica L. and intercropping for the sustainable control of aphid Toxoptera aurantii (Hemiptera: Aphididae) in Rwanda. PhD Thesis, UCL-Université Catholique de Louvain

Hindorf H, Omondi CO (2011) A review of three major fungal diseases of Coffea arabica L. in the rainforests of Ethiopia and progress in breeding for resistance in Kenya. J Adv Res 2:109–120

Jaramillo J, Muchugu E, Vega FE, Davis A, Borgemeister C, Chabi-Olaye A (2011) 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 6:e24528

Jezeer RE, Verweij PA, Boot RG, Junginger M, Santos MJ (2019) Influence of livelihood assets, experienced shocks and perceived risks on smallholder coffee farming practices in Peru. J Environ Manag 242:496–506

Jha S, Bacon CM, Philpott SM, Ernesto Méndez V, Läderach P, Rice RA (2014) Shade coffee: update on a disappearing refuge for biodiversity. Bioscience 64:416–428

Jimenez-Soto E (2020) The political ecology of shaded coffee plantations: conservation narratives and the everyday-lived-experience of farmworkers. J Peasant Stud. https://doi.org/10.1080/03066150.2020.1713109

Jonsson M, Raphael IA, Ekbom B, Kyamanywa S, Karungi J (2015) Contrasting effects of shade level and altitude on two important coffee pests. J Pest Sci 88:281–287

Karp DS, Mendenhall CD, Sandí RF, Chaumont N, Ehrlich PR, Hadly EA, Daily GC (2013) Forest bolsters bird abundance, pest control and coffee yield. Ecol Lett 16:1339–1347

Karungi J, Nambi N, Ijala AR, Jonsson M, Kyamanywa S, Ekbom B (2015) Relating shading levels and distance from natural vegetation with hemipteran pests and predators occurrence on coffee. J Appl Entomol 139:669–678

Kebati RK, Nyangeri J, Omondi CO, Kubochi JM (2016) Effect of artificial shading on severity of coffee berry disease in Kiambu County, Kenya. Annu Res Rev Biol 9(2):1–11. https://doi.org/10.9734/ARRB/2016/23326

Knolhoff LM, Heckel DG (2014) Behavioral assays for studies of host plant choice and adaptation in herbivorous insects. Annu Rev Entomol 59:263–278

Kremer JMM, Nooten SS, Cook JM, Ryalls JMW, Barton CVM, Johnson SN (2018) Elevated atmospheric carbon dioxide concentrations promote ant tending of aphids. J Anim Ecol 87:1475–1483

Krishnan S (2017) Sustainable coffee production. Oxford research encyclopedia of environmental science. Oxford University Press

Kumar B (2016) Biocontrol of insect pests. Ecofriendly pest management for food security. Elsevier, pp 25–61

Kutywayo D, Chemura A, Kusena W, Chidoko P, Mahoya C (2013) 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 8:e73432

Lamichhane JR, Barzman M, Booij K, Boonekamp P, Desneux N, Huber L, Kudsk P, Langrell SRH, Ratnadass A, Ricci P et al (2015) Robust cropping systems to tackle pests under climate change. Rev Agron Sustain Dev 35:443–459

Latini AO, Silva DP, Souza FML, Ferreira MC, de Moura MS, Suarez NF (2020) Reconciling coffee productivity and natural vegetation conservation in an agroecosystem landscape in Brazil. J Nat Conserv 57:125902

Leite SA, dos Santos MP, da Costa DR, Moreira AA, Guedes RNC, Castellani MA (2021) Time-concentration interplay in insecticide resistance among populations of the Neotropical coffee leaf miner, Leucoptera coffeella. Agric for Entomol 23:232–241

Lenné JM, Wood D (2011) Agrobiodiversity management for food security: a critical review. CABI, Wallingford
Lomelí-Flores JR, Barrera JF, Bernal JS (2010) Impacts of weather, shade cover and elevation on coffee leafminer Leucoptera coffeella (Lepidoptera: Lyonetiidae) population dynamics and natural enemies. Crop Prot 29:1039–1048
López-Bravo DF, de Virginio-Filho EM, Avelino J (2012) Shade is conducive to coffee rust as compared to full sun exposure under standardized fruit load conditions. Crop Prot 38:21–29
Mahdhi M, Tounekti T, Al-Turki TA, Khemira H (2017) Composition of the root mycorrhizal community associated with coffea arabica in Fifa mountains (Jazan region, Saudi Arabia). J Basic Microbiol 57:691–698
Mariño YA, Pérez M-E, Gallardo F, Trifilio M, Cruz M, Bayman P (2016) Sun vs. shade affects infestation, total population and sex ratio of the coffee berry borer (Hypothenemus hampei) in Puerto Rico. Agric Ecosyst Environ 222:258–266
Mazzafera P, Robinson SP (2000) Characterization of polyphenol oxidase in coffee. Phytochemistry 55:285–296
Melo GA, Shimizu MM, Mazzafera P (2006) Polyphenoloxidase activity in coffee leaves and its role in resistance against the coffee leaf miner and coffee leaf rust. Phytochemistry 67:277–285
Metcalf RL, Luckmann WH (1994) Introduction to insect pest management. John Wiley & Sons
Michereff MFF, Filho MM, Blassioli-Moraes MC, Laumann RA, Diniz IR, Borges M (2015) Effect of resistant and susceptible soybean cultivars on the attraction of egg parasitoids under field conditions. J Appl Entomol 139:207–216
Milligan MC, Johnson MD, Garfinkel M, Smith CJ, Njoroge P (2016) Quantifying pest control services by birds and ants in Kenyan coffee farms. Biol Cons 194:58–65
Mitiku F, Nyssen J, Maertens M (2018) Certification of semi-forest coffee as a land-sharing strategy in Ethiopia. Ecol Econ 145:194–204
la Mora AD, Livingston G, Philpott SM (2008) Arboreal ant abundance and leaf miner damage in coffee agroecosystems in Mexico. Biotropica 40:742–746
Morris JR, Perfecto I (2016) Testing the potential for ant predation of immature coffee berry borer (Hypothenemus hampei) life stages. Agr Ecosyst Environ 233:224–228
Mosomtai G, Azrag AGA, Babin R, Abdel-Rahman EM, Odindi J, Mutanga O, Tonnang HEZ, Landmann T, David G (2021) Functional land cover scale for three insect pests with contrasting dispersal strategies in a fragmented coffee-based landscape in Central Kenya. Agr Ecosyst Environ 319:107558
Mosomtai G, Odindi J, Abdel-Rahman EM, Babin R, Fabrice P, Mutanga O, Tonnang HE, David G, Landmann T (2020) Landscape fragmentation in coffee agroecological subzones in central Kenya: a multiscale remote sensing approach. J Appl Remote Sens 14:044513
Mouen Bedimo JA, Bieysse D, Njiayouom I, Deumeni JP, Cilas C, Nottéghem JL (2007) Effect of cultural practices on the development of arabica coffee berry disease, caused by Colletotrichum kahawae. Eur J Plant Pathol 119:391
Muschler RG (2001) Shade improves coffee quality in a sub-optimal coffee-zone of Costa Rica. Agrofor Syst 51:131–139
Nair KP (2021) Coffee. In: Nair KP (ed) Tree crops : harvesting cash from the world's important cash crops. Springer International Publishing, Cham, pp 215–248
Narango DL, Tallamy DW, Snyder KJ, Rice RA (2019) Canopy tree preference by insectivorous birds in shade-coffee farms: Implications for migratory bird conservation. Biotropica 51:387–398
Ngango J, Kim SG (2019) Assessment of technical efficiency and its potential determinants among small-scale coffee farmers in Rwanda. Agriculture 9:161
Ngowi AVF, Maeda DN, Wesseling C, Partanen TJ, Sanga MP, Mbise G (2001) Pesticide-handling practices in agriculture in tanzania: observational data from 27 coffee and cotton farms. Int J Occup Environ Health 7:326–332
Ortega DL, Bro AS, Clay DC, Lopez MC, Tuyisenge E, Church RA, Bizoza AR (2019) Cooperative membership and coffee productivity in Rwanda's specialty coffee sector. Food Secur 11:967–979
Otieno HMO, Alwenge BA, Okumu OO (2019) Coffee production challenges and opportunities in tanzania: the case study of coffee farmers in Iwindi, Msia and Lwati Villages in Mbeya Region. Asian J Agric Hortic Res. https://doi.org/10.9734/ajahr/2019/v3i229993
Pak D, Iverson AL, Ennis KK, Gonthier DJ, Vandermeer JH (2015) Parasitoid wasps benefit from shade tree size and landscape complexity in Mexican coffee agroecosystems. Agr Ecosyst Environ 206:21–32
Perfecto I, Hajian-Forooshani Z, White A, Vandermeer J (2021) Ecological complexity and contingency: Ants and lizards affect biological control of the coffee leaf miner in Puerto Rico. Agr Ecosyst Environ 305:107104
Peterson JA, Ode PJ, Oliveira-Hofman C, Harwood JD (2016) Integration of plant defense traits with biological control of arthropod pests: challenges and opportunities. Front Plant Sci 7:1794
Philpott SM, Armbrecht I (2006) Biodiversity in tropical agroforests and the ecological role of ants and ant diversity in predatory function. Ecol Entomol 31:369–377
Rahn E, Liebig T, Ghazoul J, van Asten P, Läderach P, Vaast P, Sarmiento A, Garcia C, Jassogne L (2018) Opportunities for sustainable intensification of coffee agroecosystems along an altitudinal gradient on Mt. Elgon, Uganda. Agr Ecosyst Environ 263:31–40
Ratnadass A, Fernandes P, Avelino J, Habib R (2012) Plant species diversity for sustainable management of crop pests and diseases in agroecosystems: a review. Agron Sustain Dev 32:273–303
Rezende MQ, Venzon M, dos Santos PS, Cardoso IM, Janssen A (2021) Extrafloral nectary-bearing leguminous trees enhance pest control and increase fruit weight in associated coffee plants. Agr Ecosyst Environ 319:107538
Ribas AF, Pereira LFP, Vieira LGE (2006) Transformação genética de café. Braz J Plant Physiol 18:83–94
Rice RA (2018) Coffee in the crosshairs of climate change: agroforestry as abatis. Agroecol Sustain Food Syst 42:1058–1076
Righi CA, Campoe OC, Bernardes MS, Lunz AMP, Piedade SMS, Pereira CR (2013) Influence of rubber trees on leaf-miner damage to coffee plants in an agroforestry system. Agrofor Syst 87:1351–1362
da Rosado MC, de Araújo GJ, Pallini A, Venzon M (2021) Cover crop intercropping increases biological control in coffee crops. Biol Control 160:104675
Schmitz OJ, Barton BT (2014) Climate change effects on behavioral and physiological ecology of predator–prey interactions: implications for conservation biological control. Biol Control 75:87–96
Sera GH, Sera T, Ito DS, Ribeiro Filho C, Villacorta A, Kanayama FS, Alegre CR, Del Grossi L (2010) Coffee berry borer resistance in coffee genotypes. Braz Arch Biol Technol 53:261–268
Simms EL, Fritz RS (1990) The ecology and evolution of host-plant resistance to insects. Trends Ecol Evol 5:356–360
Sinu PA, Viswan G, Fahira PP, Rajesh TP, Manoj K, Hariraveendra M, Jose T (2021) Shade tree diversity may not drive prey-predator interaction in coffee agroforests of the Western Ghats biodiversity hotspot. India Biol Control 160:104674
Teixeira HM, Bianchi FJJA, Cardoso IM, Tittonell P, Peña-Claros M (2021) Impact of agroecological management on plant diversity and soil-based ecosystem services in pasture and coffee systems in the Atlantic forest of Brazil. Agr Ecosyst Environ 305:107171

Tougeron K, Hance T (2021) Cascading effects of caffeine intake by primary consumers to the upper trophic level. Bull Entomol Res. https://doi.org/10.1017/S0007485321000687

Tscharntke T, Clough Y, Bhagwat SA, Buchori D, Faust H, Hertel D, Hölscher D, Juhrbandt J, Kessler M, Perfecto I et al (2011) Multifunctional shade-tree management in tropical agroforestry landscapes—a review. J Appl Ecol 48:619–629

Tumwebaze SB, Byakagaba P (2016) Soil organic carbon stocks under coffee agroforestry systems and coffee monoculture in Uganda. Agr Ecosyst Environ 216:188–193

Van Asten P, Wanyama I, Mukasa D, Nansamba R, Kisaakye J, Sserubiri I, Bongers G, Jassogne L (2012) Mapping and evaluating improved intercrop and soil management options for Ugandan coffee farmers. In: Technical report. Project executed by the international institute of tropical institute. Funded by livelihoods and enterprises for agricultural development (LEAD). 90

Vandermeer J, Perfecto I, Philpott S (2010) Ecological complexity and pest control in organic coffee production: uncovering an autonomous ecosystem service. Bioscience 60:527–537

Vega FE, Brown SM, Chen H, Shen E, Nair MB, Ceja-Navarro JA, Brodie EL, Infante F, Dowd PF, Pain A (2015a) Draft genome of the most devastating insect pest of coffee worldwide: the coffee berry borer. Hypothenemus Hampei Sci Rep 5:12525

Vega FE, Infante F, Johnson AJ (2015b) Chapter 11—The genus hypothenemus, with emphasis on H. hampei, the coffee berry borer. In: Vega FE, Hofstetter RW (eds) Bark beetles. Academic Press, San Diego, pp 427–494

Ventocilla MC, Grossi A, Hernandez-Aguilera JN, Dinku T, Recha J, Ambaw G (2020) Brewing resilience for Ethiopia's smallholder coffee farmers: a closer look at Ethiopia's coffee sector to help address climate information gaps

Verburg R, Rahn E, Verweij P, van Kuijk M, Ghazoul J (2019) An innovation perspective to climate change adaptation in coffee systems. Environ Sci Policy 97:16–24

van der Vossen H, Bertrand B, Charrier A (2015) Next generation variety development for sustainable production of arabica coffee (Coffea arabica L.): a review. Euphytica 204:243–256

Weber J, Halsall CJ, Muir D, Teixeira C, Small J, Solomon K, Hermanson M, Hung H, Bidleman T (2010) Endosulfan, a global pesticide: a review of its fate in the environment and occurrence in the Arctic. Sci Total Environ 408:2966–2984

Zaro GC, Caramori PH, Yada Junior GM, Sanquetta CR, Nunes AL, Prete CE, Voroney P (2020) Carbon sequestration in an agroforestry system of coffee with rubber trees compared to open-grown coffee in southern Brazil. Agrofor Syst 94:799–809