Review

The role of agroforestry systems in reconciling food and cocoa (*Theobroma cacao* L.) and coffee (*Coffea* spp. L.) production in a changing environment

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Perennial export crops such as cocoa (*Theobroma cacao* L.) and coffee (*Coffea* spp. L.) contribute indirectly to food security by providing an income that can be used to buy food, household goods and/or supplies for the cultivation of basic food crops. Thus, any perennial crop loss incurred due to the effects of climate change will also negatively impact food security and, more generally, the livelihoods of smallholders, farmers and rural communities. It is foreseen that in the not so distant future (2050), climate change and increased land use for food crop production, to meet increasing demands for food as the world's population increases, will negatively impact global production of perennial crops such as coffee and cocoa by reducing the availability of land suitable for their cultivation. Furthermore, the current trend towards full sun systems with excessive use of external inputs (agrochemicals, irrigation) increases the vulnerability of the cocoa and coffee sectors to climate change. To reconcile the need for food crops and the demand for export crops such as coffee and cocoa, under the scenarios of climate change and population growth, innovative production systems have to be developed. Such systems should also contribute to the mitigation of and adaptation to climate change and provide other ecosystem services such as regulation of pests and diseases. Agroforestry systems are some of the production systems which can address these manifold demands. Here, ideas for the development of competitive and sustainable agroforestry systems and the evaluation of their environmental benefits are presented and reviewed.

Agriculture has supported the development of modern civilization, and significant advances, over time, have changed the face of agriculture in a technologically-driven world. Currently, global food security is being threatened by numerous factors, including climate change. Climate (as weather averaged over at least 30-year periods (Allwood et al. 2014)) is dependent on the fluctuation of many factors, nearly all of which are dynamic over geological time spans. A changing climate is therefore to be expected. Global warming trends, increasing sea levels, decreasing snow and ice levels and changing rainfall patterns have been recorded and partly attributed to anthropogenic activities (IPCC 2013; Cai et al. 2014; Pendergrass and Hartmann 2014). Agriculture is not only affected by such climatic events, but also contributes to climate change. The need to alleviate hunger, provide suitable nourishment and ensure a sustainable standard of living for the world's population persists in the face of the changing climatic environment. FAO has reported that the world's population is expected to increase to 9 billion by 2050, and it is estimated that a 60-70% global increase in food production is needed to feed this growing population. Ten percent of the global population experienced severe food insecurity in 2017, and world hunger has increased for the third consecutive year (FAO et al. 2018). Key drivers in this trend have been recent climate variations and extreme weather events and increasing impacts of pests and diseases (P&D). Global changes of concern also include the continuous reduction of the available arable land and the intensification of agriculture with increasing use of inputs (fertilizers, pesticides, water), from limited resources. The non-sustainability of this trend is obvious.

Ericksen et al. (2009) highlighted the need to adapt food systems to these global environmental changes, and suggested that this requires more than just technological solutions to increase agricultural yields. The paradigm shift that has occurred included the promotion of agroecology. Sustainable innovative farming systems are required, which use fewer inputs, and incorporate increased biodiversity and biotic interactions. Unfortunately, the contribution of perennial export crops in some of the proposed farming systems is often overlooked (Vermeulen et al. 2012) while the focus is on the cultivation of food crops such as grain or soy (Shindell et al. 2012). It is thus necessary to reconcile the cultivation of food along with export crops, such as cocoa and coffee, while addressing the effects of climate change. An approach towards achieving this through the adoption of agroforestry systems (AFS) is the subject of this analytical review.

Coffee and Cocoa production

Over the last few years, alarming messages about the future of coffee, chocolate and even beer have appeared in the international press (Guardian 2015; ThePrint 2018), stating that these indulgences would become either very costly or might even disappear. Headlines such as "*Cocoa may go extinct by 2050*" (ThePrint 2018) raised the alarm. Even though these messages are exaggerated, there is a grain of truth in them (Ramirez-Villegas and Thornton 2015; Bunn et al. 2018a, b; WCF 2018; Xie et al. 2018). There are indeed valid concerns regarding coffee (*Coffea* spp. such as *Coffea arabica and C. canephora (*syn. *C. robusta*)) and cocoa (*Theobroma cacao* L.) production being able to meet the steadily increasing global demand. Moreover, the main factors responsible for food insecurity according to FAO (2018), *viz.,* climate variations, extreme weather events and increasing impacts of pests and diseases, also negatively affect coffee and cocoa production.

The production of export crops such as coffee and cocoa is essential to the livelihood of 160-170 million people worldwide (Fountain and Hütz-Adams 2015; ICO undated). Coffee ranks as the second largest globally-traded commodity (just after crude oil), and is grown in more than 60 tropical countries (Waller et al. 2007). Latin-America and Asia are responsible for about 75% of the world´s coffee production (ICO undated). The West African cocoa belt (from Cote d'Ivoire to Cameroon) accounts for over 70% of the world´s cocoa production (ICCO 2018).

Coffee and cocoa are clear examples of tropical perennial export crops where yields are below their potential. Improving productivity of these export crops and other tropical food crops can reduce rural poverty and increase food security. Whilst the causes of low productivity are complex, one major contributory factor is crop losses due to plant health problems. Accurate information on the extent of these losses is scarce, but estimates of losses of 30-40% annually are not uncommon (Savary et al. 2019). In addition to decreasing yield (Strange and Scott 2005), P&D also reduce quality of crops, and farmers' revenues due to attendant lower farm gate prices.

Climate change and climate variability are expected to exacerbate the effect of P&D on coffee and cocoa production (Jarvis et al. 2008; Avelino et al. 2015; Gateau-Rey et al. 2018). A first clear warning of the impact of climate change on coffee production was provided by the recent coffee leaf rust disease crisis in Central America. The ravages of this disease, which was putatively caused by factors such as climate change, resulted in losses in revenue of over €850 million between 2011-2013 (Avelino et al. 2015). Coffee production decreased by 16% in 2012-2013 and by a further 10% in 2013-2014 as a consequence of the epidemic. In Central America, these losses negatively affected the livelihoods of approximately 500,000 smallholders and producers as well as the food security situation of these rural communities. The same phenomenon has been observed in Vietnam where drought, due to a longer than usual dry season, together with more erratic rainfall, resulted in exacerbated coffee root damage by nematodes and fungal diseases and an approximate decrease of 25% in *Robusta* coffee production in 2015 (MARD 2015). This amounts to an economic loss of about €1 billion from a previous export value of €3.2 billion (MARD 2015). In both Central America and Vietnam, these production reductions had direct impacts on the livelihoods of hundreds of thousands of smallholders and producers; approximately 500,000 in Central America (Avelino et al. 2015) and 650,000 in Vietnam (MARD 2015). For these rural households, coffee is often the only source of income which meets all of the living expenses, including those associated with the purchase of supplies required for the cultivation of basic food crops. In Africa and Asia, food expenditure can exhaust more than 50% of total household income. The aforementioned shortfalls in crop production, and the associated revenue generated, thus significantly jeopardized the food security of these rural communities. Moreover, the reduced supply of coffee affected the national economies, consumers and the international coffee industry.

Concomitantly, the continued increase in demand for coffee and cocoa has led to increased deforestation. The latter is a driver of climate change (Ruf et al. 2015). Hardner and Rice (2002) estimated that coffee and cocoa alone have replaced 20 million hectares of tropical habitat in areas with spatial overlap with biodiversity hotspots.

Climate change will have an impact on the suitability of current coffee and cocoa production areas (Läderach et al. 2013; Rahn et al. 2013; Ramirez-Villegas and Thornton 2015; Läderach et al. 2017; Bunn et al. 2018a). For example, a reduction in suitable growing areas for *Coffea arabica* in Ethiopia is projected to occur with increasing temperatures. Cultivation of this species may thus need to be shifted towards higher elevations and more heat-tolerant *Coffea robusta* may be required at altitudes of less than 1500 metres above sea level (Ramirez and Thornton 2015). Although in many cases the impacts of climate change on suitability of growing areas for coffee and cocoa are not clearly positive or negative (Bunn et al. 2018a), the aforementioned shift in suitability for coffee cultivation in Ethiopia, may put additional pressure on montane forest areas (Rahn et al. 2013). Climate change can thus be regarded as both a result of deforestation, which decreases carbon sequestration, and a contributor to it, where coffee cultivation supplants forest cover.

The increased demand for food, due to the aforementioned population growth trend as well as economic expansion, will put additional pressure on already limited available arable land, water and energy, especially in Africa, where population growth will be much higher than forecasted 20 years ago (Zinkina and Korotayev 2014). Further research is therefore required to investigate how population growth, and thus the increased demand for food crops, will impact production of perennial export crops such as coffee and cocoa.

A bleak future?

It has been stated above, that in the not so distant future (by 2050), climate change and increased land use for food crop production, to meet increasing demands for food as the world's population increases, will negatively impact global production of perennial crops such as coffee and cocoa by reducing the amount of land available for their cultivation (Bunn et al. 2015; Rahn et al. 2013; Schroth et al. 2016). The current trend towards full sun systems with excessive use of external inputs (agrochemicals, irrigation) increases the vulnerability of the cocoa and coffee sectors to climate change and allied consequences of P&D. In addition, the reliance on agrochemicals for P&D control has negative impacts on the resilience of the coffee and cocoa landscapes and the safety of producers and consumers (Brown et al. 2018).

However, the conditions for sustainable production of cocoa and coffee, in the face of climate change, are still to be met. Important structural changes in these two perennial crop industries are critically needed to reach this goal. These changes are necessary to ensure the economic viability of cocoa and coffee farming systems, rational land use and mitigation of the ecological impact of the current agricultural practices. The implementation of changes requires specific integrated programmes with a common goal of increasing economic and environmentally sustainable production on the available arable land (Wessel and Quist-Wessel 2015).

Such systems should be based on agro-ecological principles, reduce the need for external inputs and maximize production along with ecosystem services (ES) such as regulation services (climate change adaptation and mitigation measures) and biocontrol services, such as those associated with P&D control. Agroforestry-based production systems are among the production systems that can provide solutions to the aforementioned diverse demands.

Agroforestry

Agroforestry, in its most basic form, means: *Agriculture with trees*. Other definitions exist such as "*Agroforestry is a collective name for land-use systems and technologies where woody perennials (trees, shrubs, palms, bamboos, etc.) are deliberately used on the same land-management units as agricultural crops and/or animals, in some form of spatial arrangement or temporal sequence*" (FAO 2020).

In Côte d'Ivoire, both young (21-40 years-old) and old (> 55 years-old) cocoa farmers actually plan to have associated trees on their cocoa farms (Gyau et al. 2014), and this practice has been traditionally employed in Latin America, the Caribbean, Africa and Asia. It is estimated that around 70% of cocoa is produced with varying levels of shade provided by associated trees (Gockowski and Sonwa 2011; Somarriba et al. 2012; Vaast and Somarriba 2014). Although we often refer to these non-cocoa trees in cocoa agroforests as shade trees, most of these associated trees actually serve multiple purposes (Jagoret 2011; Saj et al. 2017).

Agroforestry systems (AFS) are generally complex, plurifunctional systems. An example from Cameroon showed that the associated trees in cocoa agroforests provide multiple benefits: 36% of trees produce saleable products (*e.g.* fruit), 21% generates products used for household consumption, 12% is used for wood, 11% is used to increase soil fertility, 9% has medicinal purposes, 6% has a social purpose and only 5% of associated trees is used solely to provide shade (Jagoret 2011). A recent study by Donald (2019), listed 220 reported uses of plants cultivated in biodiverse cocoa AFS in Trinidad, showing that these systems produce much more than solely cocoa. In shaded coffee plantations, the consumption and sale of coffee, fruits, timber, and other agroforestry products equal the returns from full-sun coffee plantations (Pinoargote et al. 2017). Besides providing economic benefits, as outlined by Notaro et al. (2020), associated trees in AFS also provide other environmental or ecosystem services such as the conservation of biodiversity, P&D regulation and can help to adapt to and mitigate the impact of climate change (Lasco et al. 2014; Notaro et al. 2020).

Agroforestry and climate change

As mentioned previously, climate change is both a contributor to and a result of deforestation in coffee and cocoa growing regions. It is noteworthy that coffee- and cocoa-based agroforestry can also be regarded as an adaptation and/or mitigation strategy towards climate change (Vaast et al. 2016). The sequestering of carbon in the shade component of an AFS, as well as that in the soil of these perennial systems, is an obvious mitigation factor (Middendorp et al. 2018; Rice 2018). A study by Saj et al. (2017) demonstrated the potential for carbon storage in cocoa-based agroforests. They showed that, in Cameroon, cacao biomass, associated tree biomass and total (associated + cacao) tree biomass steadily increased with the age of the agroforestry system. At old (41-60 years-old) and very old stages (>60 years-old), total tree biomass in AFS was not significantly different from the biomass in a forest control, whilst it was lower at the immature (<11 years-old) and young stages (11<20 years-old) (Saj et al. 2017). A study by Pinoargote et al. (2017) showed that carbon stocks in coffee increased from full sun, to simple shade canopies, to complex, multi-strata shade canopies and ranged from 8.8–38.6 Mg ha^{-1}. Rahn et al. (2013) showed that afforestation of degraded areas with coffee AFS and boundary tree plantings resulted in the highest synergies between adaptation and mitigation for climate change.

The shade provided by associated species also affects the microclimate, such as temperature, humidity and light availability (Abdulai et al. 2018), which in turn can influence the productivity of the system, either directly by reducing physiological stress of the perennial crop (Abdulai et al. 2018) or indirectly by affecting crop losses due to P&D (Babin et al. 2010; Gidoin et al. 2014). However, the effects of microclimate on the productivity of the system are many and diverse and depend on the biophysical context in which a particular production system is found. Abdulai et al. (2018) found that under sub-optimal and extreme climate conditions, cocoa agroforestry is less resilient than systems with cocoa in full sun. Lahive et al. (2019), in a review on the physiological response of cacao to the environment, found that the complexity of the cacao/shade tree interaction can lead to contradictory results and that our understanding of the impact of AFS on cacao physiology needs to be expanded. How climate change will impact coffee- and cocoa- based AFS, as a whole, also remains a subject that requires further research (Luedeling et al. 2014).

Agroforestry and pest and disease management

The high vulnerability of agroecosystems to pests and diseases has been ascribed to simplification of these systems, and the concomitant loss of biodiversity (Avelino et al. 2011). Increasing biodiversity has thus been proposed to decrease pest and disease risks. Ratnadass et al. (2012) presented an overview of the myriad ways in which biodiversity can reduce pest and disease risks. Agroforestry systems, which are naturally more (bio) diverse than full sun systems, are thus expected to provide P&D regulation services.

Gidoin et al. (2014) showed how associated tree spatial structure, host composition, and resource availability influenced the density of a cocoa pest, the mirid (*Sahlbergella singularis*), and cocoa black pod (a disease caused by *Phytophthora megakarya*) prevalence in cacao agroforests in Cameroon. They found that mirid density decreased when a minimum number of randomly distributed forest trees was present compared with the aggregated distribution of forest trees, or when forest tree density was low. Schroth et al. (2000) provided an overview of the different mechanisms underlying P&D regulation in agroforestry systems. Pumariño et al. (2015), in a meta-analysis on the effects of agroforestry on pest, disease and weed control, showed that in perennial crops such as coffee and cocoa, agroforestry was associated with lower pest abundances and a lower incidence of plant damage.

Climate change can also impact losses due to P&D in coffee and cacao agroforestry systems. Gateau-Rey et al. (2018) showed that drought severely decreased cocoa yield (89%) and increased infection rate of the chronic fungal disease, 'witches' broom' (caused by the pathogen, *Moniliophthora perniciosa*), in cocoa agroforests in Bahia, Brazil. Avelino et al. (2015) showed how climate change influenced the coffee leaf rust epidemics between 2011-2013. Agroforestry systems could also limit, to some extent, such losses. Mouen Bedimo et al. (2008) showed a reduction in coffee berry disease (CBB) on coffee trees grown under shade compared with those grown in full sunlight. The associated trees acted on certain environmental parameters to limit disease incidence.

However, given the complex mechanisms that regulate P&D dynamics in AFS (Cerda 2017), the impact of associated trees on pest and disease regulation is *a priori* uncertain and varies according to scale (tree plot or landscape level).

Agroforestry: food production and other services

Perennial export cash crops, such as coffee and cocoa, provide an income that can be used to ensure food security as it facilitates the purchase of food or the basic inputs to produce food crops, provided both are actually available on the market (Bymolt et al. 2018). Indirect benefits are also derived by providing habitats for wildlife and these animals may be used as a food source. Coffee- and cocoa-based AFS also directly contribute to food security through the direct provision of food from flowers, fruits and leaves of trees and by supporting staple crop production (Jamnadass et al. 2013; Cerda et al. 2014; Jemal et al. 2018). Jemal et al. (2018), in a study in Ethiopia, identified 127 useful plant species in specific AFS, 80 of which were identified as edible species with 55 being cultivated primarily for household food supply. Cerda et al. (2014) found that, in Central America, the main contribution of agroforestry farming to small farmers' families was the generation of both cash income and products for domestic consumption. Seasonality in fruit production can also assure access to fruits throughout the year in systems with diverse fruit trees (Jamnadass et al. 2011). These systems can also contribute to rural households by providing fuel for cooking (Jamnadass et al. 2013, Cerda et al. 2014) and by supporting various ecosystem services (ES), such as pollination, which are essential for the production of some food plants (Priess et al. 2007; Notaro et al. 2020).

Optimizing multi-service provisioning by agroforestry systems

Agroforestry systems thus provide multiple ES. According to Perfecto and Vandermeer (2015), coffee agroecosystems have repeatedly shown that shaded and more diverse coffee systems provide a higher degree of pest control, climatic resistance and pollination services. In Costa Rica, a greater diversity and number of pollinators visiting coffee plants were observed on coffee farms located close to forested areas, which translated into increased coffee yields and improved coffee quality (FAO 2009).

However, the trade-offs among these services is often poorly understood. Assessment of AFS management optimization paths is still uncommon (Andreotti et al. 2018; Notaro et al. 2020). Such optimization pathways are necessary in order to achieve the ''win–win–win–win'' approach advocated by Scherr et al. (2010), which combines productivity and income generation, ecosystem services, food security, and climate regulation. Andreotti et al. (2018) explored an innovative method to identify management schemes that favour the multifunctionality of complex AFS. They used ground truth data from Cameroon to study three services: cocoa production, above-ground tree carbon storage and natural pest control. The innovative use of Pareto front algorithms allowed novel insights into the combined provision of multiple ecosystems services. The results indicated that there were trade-offs among services and this knowledge is useful to further optimize the provisioning of these services.

Conclusion

According to the World Agroforestry Center « *Agroforestry is a sustainable, proven and efficient land management system. However, despite proven benefits, agroforestry does not receive the attention it deserves and investments in agroforestry are insufficient* » (SIANI 2018).

Here it has been shown that cocoa and coffee-based agroforestry systems are indeed a promising option available to achieve Scherr et al.'s (2010) win-win-win-win approach, integrating productivity and income generation, ecosystem services, food security, and climate regulation. Such AFS could allow for continued provisioning of coffee and cocoa while simultaneously ensuring a living income for farmers, and adapt to and mitigate the impact of climate change. However, these AFS are not adapted to all conditions and should be seen as complementary to conventional agroecosystems. Most importantly, these AFS should be adapted to farmers' strategies and objectives. Therefore, we should continue to look for the best alternatives customized to farmers' particular needs. As Cathy Pieters, Director of Mondelez's *Cocoa Life* programme, stated at the World Cocoa conference in Berlin, in May 2018,*".......I think we might be artificially keeping families in cocoa, who might be better off in other things had they been given the choice"*.

However, an optimistic approach is recommended and efforts to mitigate the effects of climate change, as prescribed by Shindell et al. (2012), should be sustained so that they can improve human health and food security with Scherr et al.'s (2010) win-win-win-win approach. This should be achievable through climate-smart and sustainable approaches such as agroforestry.

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