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Review Article

The Benefits of Agroforestry Coffee Production Systems: A Review

Kalifa Nasiro*

Department of Coffee Agronomy, Ethiopian Institute of Agricultural Research, Jimma Agricultural Research Center, Addis Ababa, Ethiopia

Abstract

Coffee is one of the most popular beverages worldwide and is consumed by approximately one-third of the world's population. More than 80 developing countries have earned foreign currency from coffee. Coffee production systems vary from multi-strata agroforestry systems to full-sun monocultures. This literature review aimed to explore the benefits of agroforestry coffee production systems, in which coffee trees are planted together with forest trees, fruits, and timber trees. The question of whether coffee trees benefited from shade trees has not been clear for more than a century. Yield potential, competition for water and nutrients, and perceived lower economic performance compared to high-input monoculture coffee systems are central issues in this controversy. However, various case studies provide evidence that the economic performance of coffee agroforestry systems is equal to or better than that of unshaded plantations and/or plantations with higher input levels. Additionally, agroforestry systems provide several ecosystem services that might help sustain the production of multiple crops, improve farmers' livelihoods, and conserve biodiversity. In the face of climate change and the resulting rainfall decline and increased fluctuations in temperature extremes, tree shade appears to be an important climate adaptation coping strategy for smallholder farmers. Thus, shade can reduce the ecological and economic vulnerability of resource-poor smallholder farmers. Because of the long periods involved in tree growth, our understanding of agroforestry systems will be restricted if it depends only on experimental data. One way to improve our understanding and integrate scattered knowledge on coffee agroforestry is by using process-based models. Therefore, for the effective prediction of coffee growth dynamics, future research should integrate modeling that bridges gaps and can set the development of quantitative models predicting the growth and production of coffee.

Keywords

Agroforestry, Arabica Coffee, Modeling, Productivity, Quality

1. Introduction

Coffee is one of the most popular beverages worldwide consumed by about one-third of the world's population. Its popularity and volume of consumption are growing annually, and coffee shops are the fastest-growing restaurant business. Today, coffee is both a part of our social experience and an accepted norm for conducting business. Coffee is the second most exported commodity after oil and employs over 100 million people worldwide [40]. More than 80 developing countries mainly earn their foreign currency from coffee. In 2015, coffee generated over US$ 39.3 billion in export revenue for many

*Corresponding author: nasirokalifa@gmail.com (Kalifa Nasiro)

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developing countries [45]. In the same year, Ethiopia was the fifth exporter of coffee in the world, contributing approximately 4.5% of the world's total coffee production [45]. Coffee is an important export commodity for the Ethiopian economy, accounting for approximately 25-30% of total exports in 2015 [43] and 10% of the country's GDP [39]. There is even a popular saying, "Coffee is the backbone of our life," meaning how the crop is so closely interlinked with the livelihoods of many smallholder farmers, and many others derive their livelihood from coffee production, processing, and marketing services from these systems [65].

Coffee production systems vary from multi-strata agroforestry systems to full-sun monocultures. In agroforestry coffee production systems, coffee trees are planted together with forest trees or within leguminous trees, fruits, timber, and firewood, usually with a high density and diversity of shade trees. Such systems often have a large diversity of fauna and flora, and provide local and regional ecosystem services. Coffee is a crop grown with a large variation in shade cover. On one extreme is traditional rustic coffee, which is planted under a forest canopy, and on the other extreme is intensive coffee agriculture, which has little or no shade cover. There is a wide range of shade systems between these two extremes [50]. In Ethiopia, coffee is grown following four management alternatives: forests, modern plantations, semi-forests, and gardens, which cover 5, 10, 35%, and 50% of the total coffee area, respectively. In forest and semi-forest systems, coffee grows naturally under the shade of native trees with minimal human intervention [39].

Heavy shading owing to reduced light penetration by the upper canopy strata can result in increased competition for light for photosynthesis. Subsequently, the undesirable growth of single-stemmed coffee trees with thin leaves and reduced reproductive efficiency was evident. Again, dark respiration can result in the death of heavily shaded productive middle and bottom primary branches, and thus, the productivity of the coffee tree considerably decreases [96]. However, in the garden system, coffee is mostly grown in the shade of low-density trees, which corresponds to a typical example of agroforestry systems with intensive traditional human interventions. Even though coffee is said to be a shade-loving crop, in many situations, modern coffee cultivars can be grown in full sun with appropriate plant and soil management, and even yield shaded coffee. In recent years, large areas of coffee monoculture plantations have been installed with the main objective of maximizing yields using agronomic practices such as improved seedlings, pruning, and weeding [39]. Coffee production in full sunlight has been highly successful because of the high acclimation capacity of coffee plants to different irradiance regimes, involving changes in physiological, anatomical, and ultrastructural characteristics [35].

However, unshaded plantations generally require high levels of external inputs to maximize crop yield and are often associated with soil degradation and environmental pollution. In addition, smallholder producers of unshaded coffee face serious economic risks related to high variable costs and unstable market prices. In addition, sun plantations typically experience greater runoff and nutrient leaching, and remain productive for only one-third to one-half as long as comparable shaded plantations [97]. In full sun conditions, there are inadequate reaction centers to accommodate the light energy and convert it into biochemical energy, and the coffee plant photo respires excessively; eventually, most of the stored carbohydrates are depleted, which ultimately leads to shoot and root die-backs. In addition, excessive evapotranspiration and severe water stress, death of actively growing shoot parts such as branch tips, seasonal crinkling of leaves, frost damage, "hot and cold disorder," and subsequent yield reduction are common problems in unshaded coffee stands [28, 34].

Hence; due to these positive effects, agroforestry-based coffee production has been considered a potential practice for tackling climate change's negative impacts [66] and has been strongly suggested as an adaptation strategy for ensuring sustainable coffee production in the future [43]. However, there is no agreement on what the optimum shade regime may be for coffee because shade effects change according to regional conditions, such as altitude, latitude, light intensity or temperature, cloud cover, soil fertility, management, and coffee variety. Although shade cover can be beneficial for coffee growth and production under suboptimal climatic conditions [58], it is important to regulate the amount of shade. Consequently, the level of shading should be neither excessive for adequate coffee productivity nor too low for effective protection of coffee plants against harmful environmental conditions [71].

In a scenario of increasing global climate change and climate instability, it is necessary to find sustainable and financially viable coping strategies for small farmers who have limited access to technological improvements [57]. From both crop production and ecological points of view, knowledge of microclimatic changes in shaded systems is needed to establish agronomically and ecologically sustainable practices [68]. Agroforestry systems may be a reasonable alternative, especially for smallholders, to ensure high revenues for farmers in the long term. This requires a review of the literature on the effects of shade on the growth, production, and physiology of coffee plants. Therefore, the objective of this review of the literature is to identify the benefits of shade trees on the microclimate, growth, and physiological response of Arabica coffee, especially in the context of sustainable production of agroforestry production systems, and to summarize and make available information on the appropriate use of shade trees in coffee production.

2. Beneficial Effects of Shade Tree for Coffee Production

Coffee evolved in the forest as an understorey tree, and thus it was considered to be shade-obligatory. According to [37], it is categorized as a shade-adapted plant species since it displays characteristic features of such species which include ability to photosynthesize in low light, high leaf area to structure ratio. According to [35], coffee plants are classified as a shade-facultative species, because they have some characteristic features of sun-adapted plants, such as increased growth and photosynthetic capacity, high light saturation under full irradiance and relatively constant quantum yield when coffee is grown in both shade (lower radiation) and full sunlight environments. In addition, coffee displays several shade-acclimation characteristics, including a low a/b ratio and structural change such as higher specific leaf [87].

Most progenies of Arabica coffee from wild coffee populations, such as germplasm collections from Ethiopia, be-severely stressed when grown without overhead shade and show low yields [101]. However, according to [101], practically all present cultivars are descendants of early coffee introductions from Ethiopia to Arabia (Yemen), where they were subjected to a relatively dry ecosystem without shade a thousand years before being introduced in Asia and Latin America. Most of these cultivars have retained the physiological attributes of shade-loving plants but can tolerate mild drought and full sunlight, although some cultivars (e.g., Typica) are not suited to the open, showing excessive symptoms of photo-damages when grown at full exposure (Figure 1). In any case, modern, high yielding coffee cultivars have been selected in test-trials with high-external inputs conducted under full sunlight and wide spacing, and hence the performance of the actual Arabica coffee cultivars is likely to have been improved at full sunlight [28].

Figure 1. *Arabica coffee is grown under open sun [28].*

If appropriately provided, the shading plantation can provide several important benefits to coffee, however, there is little knowledge on the effect of shade trees on crop production in the context of trade-offs with other management practices and the question of whether the coffee tree benefited or not from shade tree has not been clear for more than a century [27]. Perceived lower yield potential, competition for water and nutrients, and lower economic performance compared to high-input monoculture coffee systems, which is driving worldwide intensification practices of coffee systems are central issues in this controversy. However; agroforestry production systems, can provide several important benefits to coffee. It has been found to sustain coffee production and reduce biennial bearing by modifying the sink-source relationship ultimately increasing the life expectancy of the crop [73], extending coffee production to suboptimal areas, mitigating the harmful consequences of climate change and stabilizing micro-climatic condition [59], conserve biodiversity, reduces runoff and improve water infiltration, reduce high variable costs related to open-sun intensive farming [47] and improve and maintain soil fertility by way of returning large amounts of leaf litter to the underneath soil, that is, shade trees can be a valuable source of organic matter, nitrogen fixation while retaining soil moisture [35]. Also, shade may positively affect bean size and composition as well as beverage quality (lesser bitterness and astringency) by delaying and synchronizing berry flesh ripening [70].

2.1. Coffee Shade and its benEfits on Growth, Yield, and Economic Performance of Coffee

2.1.1. Response of ARABICA Coffee Growth Characters to Shade Levels

Paiva and colleagues evaluated the growth response of coffee trees grown under four shade levels (0%, 16%, 32%, and 48%) and found that there is a lack of a shade effect on the number of nodes and on production early growth stage, which indicates the existence of a period when shading does not influence coffee tree growth [75]. Coffee tree requirements for light and nutrients increase sharply after the beginning of the higher yield stage [27], usually from the third harvest. In addition, the leaves are sensitive organs to changes in the incident radiation [19]. Thus quick adaptation of leaves to conditions of low luminosity could help the trees to maintain growth levels similar to the trees under full sun. In the same period, there was a fast increase in the number of nodes and of leaf area per branch. This increase was higher than the increase in the second evaluation period, suggesting that the coffee trees in the initial growth and yield stage had a greater allocation of photosynthate for the formation of vegetative organs. In the second evaluation period, the trees exhibited a great load of berries that caused growth and vegetative development reduction [75].

A study conducted by [10] showed that Arabica coffee plants grown under 70% shade scored the highest plant height as compared to coffee plants grown under 50%, and 30% and coffee plants grown under open sun (0% shade). [11] also reported that there was a higher plant height in *C. canephora* seedlings exposed to 75% shading as compared to coffee plants grown under shade levels of 30% or in full sun. Similarly, [68] also reported that there is a tendency for increasing height by shade-adapted species for better exploitation of light penetrating from the higher stories in the canopy. A similar finding was reported by [9], plant height declined with the level of radiation. These authors also reported that coffee plants grown under open field conditions scored the minimum plant height. Generally, these results indicate that densely shaded coffee plants undergo inter-plant competition for sunlight and other growth factors, resulting in tall, but slim plants which are typically common in sun-loving crops that are grown in less than optimum light intensities [71].

On the contrary, various research findings contradict this result, and [5] showed that coffee plants grown under 90% shading level (10% solar radiation) resulted in the smallest mean plant height than plants grown under 35, 50, and 65% shading levels. [35] and [75] also observed that the highest shading levels reduced the *C. arabica* growth. As reviewed by [4], the highest shading levels reduced the growth of coffee plants [35, 75]. As reported by [96] higher shading levels by upper two to three canopy strata under forest environments reduce the growth and productivity of coffee plants. This is a result of higher shading levels that reduce both the quantity (photosynthetic photon flux density) and the quality (e.g. decreased red: far-red ratio) of the transmitted radiation, which affects the morphological and physiological processes of the plant such as photosynthesis and growth [68]. In such conditions, the plant spends much of its photosynthetic activities for maintenance purposes. Furthermore, dense shading also results in reduced coffee fruit load through its effects on coffee morphology and physiological changes, such as longer internodes, fewer nodes formed per branch, and fewer flower buds at existing nodes [24]. Because the number of nodes is the key component of coffee production, its reduction results in decreased productivity. The excessive shading reduces the quality of the transmitted radiation, which affects the physiological processes of the plant such as photosynthesis and in turn growth [68]. These contradictory results may be due to the methodological differences between the conducted works and may be due to overly higher shade levels limiting plant height and both extremes affect growth.

2.1.2. Effect of Natural Shade on the Productivity of Coffee

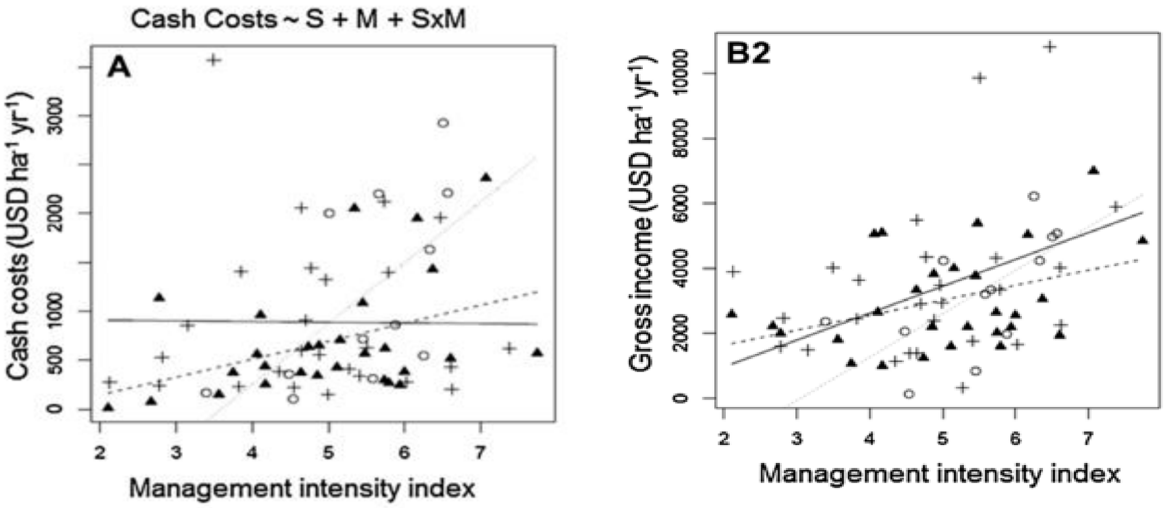
Although, the crop is said to be a shade-loving plant with greater quantum utilization efficiency for photosynthesis, excessive shading by the upper two to three canopy strata of various tree species under a forest environment would decrease the growth and productivity of coffee trees because the plant spent much of their photosynthetic activities for maintenance purpose [96]. It is possible that the low availability of photosynthetically active radiation for the shaded trees limited the stimulation necessary for the differentiation of the floral bud [27], reducing the number of berries [75]. Although the variation in the production of shaded coffee is more influenced by factors like management practices or the intensity of inputs applied than by the available radiation for the trees [17], one must consider the yield level of the studied sites. Interestingly, examining coffee management across several countries reveals that shade cover management is heterogeneous, and the changes in its coverage are region-specific. Studies conducted in Central America have shown that shade in the range of 30 –50% is beneficial at low to medium elevations. At higher elevations (>1000 m), shade can reduce yields by 20-30%. This reduction of yield at high altitudes has been attributed to the influence of shade on total tree carbon absorption, promotion of vegetative rather than flower buds, fewer nodes formed per branch, and fewer flower buds [17, 100].

As crop management is intensified, plantations have fewer shade trees, fewer shade tree species, lower canopy cover, and fewer epiphytes. Shade management intensification is often also accompanied by increased use of synthetic agrochemicals (e.g., pesticides, fungicides, herbicides, fertilizers). Finally, at the most intensified end of the crop management spectrum, coffee is grown in full sun. However, the overproduction of berries, caused by the stimulation of many floral gems in the trees subjected to high solar radiation, leads to the exhaustion of the tree reserves and hampers growth in that year and production in the following year [24]. In this way, the low production that follows a year of high production allows the recovery of nutrients and necessary growth, to bear a high berry load in the next productive cycle, causing a biennial pattern. There was a reduction of the biennial pattern in the production of coffee using shade trees, evidenced by the reduction of the biennially index in the shaded trees [27].

Shaded coffee plants can have similar rates of photosynthesis but lower bean production since lower light levels affect the development of reproductive organs and may reduce flowering [13]. However; shade-grown coffee plants experience less overbearing dieback due to enhanced vegetative growth and carbon reserves in branches and roots [109], therefore favoring long-term cherry production, which is a critically important attribute in the case of smallholder coffee farmers. Cerda and coworkers reported that agroforestry systems, besides providing several ecosystem services, did not reduce coffee yields within the studied range of shade cover (<30%) [17]. In addition, under shade, yields are more stable over time, ensuring also more stable incomes for coffee farmers [101]. In contrast, coffee plantations in full sun had more dead branches, especially with high management intensities. Consequently, reduction and higher variability in yields in subsequent years can be expected [28].

2.1.3. Effect of Natural Shade on the Economic Return of Coffee

In recent decades, there has been a transformation of coffee farming systems worldwide to more intensified systems by eliminating shade trees, increasing agrochemical inputs, and selecting genotypes [49]. This transformation is driven by the perceived higher economic performance of intensified systems, aiming to increase short-term income [101]. Economic performance indicators such as yield, costs, and profitability are important determinants for the decision-making of small-scale coffee farmers. The general perception of lower economic performance of agroforestry systems is often based on incomplete economic analyses [47]. Firstly, coffee yield is often used as the sole indicator of economic performance. Multiple studies have shown a negative relation between coffee yield and shade [70], yet this assumption is challenged by several recent studies showing that shade did not affect coffee productivity [17]. Also, despite lower coffee productivity, higher coffee prices due to improved quality or certification premiums have been linked to higher levels of shade [70]. Secondly, the costs associated with producing coffee are not always taken into account and it is debated whether these production costs of agroforestry systems are higher than those of more intensified are frequently overlooked, underestimating potential income from agroforestry plantations. The studies that include these benefits show that shade tree products can significantly contribute to farmers' income [47].



Source: [17]

Figure 2. *Effects of the double interaction type of shade × management intensity on cash costs (A), and the triple interaction altitude × type of shade × management intensity on gross income (B2).*

For agroforestry systems, both the forestry (shade tree) and the agricultural components (e.g., input use, pruning, or weeding practices) are expected to affect the productivity and economic performance of the coffee plantation and studies should reflect both simultaneously. Results of economic performance across studies suggest that intercropping coffee with shade trees shows no negative relation with the economic performance of smallholder coffee systems. Rather, income from other products, including income from timber, can provide these farmers with an extra source of income which is an opportunity to increase their economic resilience [17]. The results of a study by [48] suggest that there is no difference in economic performance between small-scale coffee plantations with different shade levels as there were no differences between net income and BCR for plantations with different shade management practices. Rather, they observed a difference in economic performance between plantations with different levels of input as net income and BCR were lower for plantations with higher input practices. These observed average BCR values (2.6 ± 3.1) are in line with findings of a recent meta-analysis, where an average BCR value of 1.9 was obtained from thirteen shaded coffee systems located in six different countries [48]. Therefore; the current review article on the economic performance of shaded coffee systems, provides evidence that the economic performance of Coffee agroforestry systems is equally good or better than that of unshaded plantations and/or with higher input levels [17] (Figure 2).

Additionally, the traditional coffee production systems provide a variety of ecosystem services that humankind relies on, including providing many non-timber forest products like spices, honey, and food in addition to coffee for local communities living in and around the forest [91]. For instance, the local communities get substantial amounts of wild food and traditional medicine from the forests. Some of the relevant species in this regard include the seeds of korarima are used as a spice widely in Ethiopian dishes and are equivalent to Indian cardamom.

2.1.4. Effect of Natural Shade on Coffee Beverage Quality and Biochemical Components

Coffee is a beverage where the flavor is the leading quality parameter and a major motivation for consumer preference and is a vital characteristic of coffee and is used to determine its price [70]. The beverage quality is centered on the description of many factors including flavor and aroma [54] which are linked to the biochemical composition of roasted beans whose presence could be favorable, for instance, trigonelline and sugars, or unfavorable in the case of caffeine and chlorogenic acids [21]. Recent work has also shown that cup quality is the result of a variety of interacting factors that include environmental conditions, field management, adequate processing and drying, and roasting. Many authors have reported the positive influence of shade on coffee quality [71, 9] reported that shade delayed ripening by one month leading to an increase in size and improvement in the biochemical composition of the coffee bean. Research related to shade effects on Catimor varieties points to shade's positive effect on coffee bean and cup quality in lower elevations and effects on cup quality that can be either positive or negative at higher elevations [24]. The shade appears to impart its greatest benefit in coffee bean flavor for plants growing in suboptimal and heat-stressed growing regions, where shade can bring environmental conditions closer to ideal levels [70]. This suggests that shade may be particularly important for maintaining coffee quality in the context of climate change, especially in regions with expected temperature increases in future climate scenarios.

In a study by [74], coffee under the *Cordia africana* shade had higher scores for flavor, acidity, and total score than coffee in full sun. Similar findings were reported by [70] who found that positive characteristics such as beverage acidity and preference were better for coffee produced under the shade of timber trees. They further observed that negative characteristics such as astringency and bitterness were higher for beverages from coffee grown in full sun. The delayed maturity between the cherry pulp and bean caused by shade is suggested as one of the reasons explaining perceived differences in beverage quality between shaded coffee and that grown in full sun. The delayed ripening leads to complete berry maturation that promotes the development of high-quality coffee flavor [67]. According to a study carried out by [74] on correlation among shade, agronomic management, and sensory variables, shade was positively and significantly correlated with acidity and body (Table 1). A positive but non-significant correlation was observed between shade and fragrance, flavor, aftertaste, balance, and the overall score.

Table 1. *Pearson's correlation coefficients of sensory variables showing the effect of shade and management levels.*

Variables	Shade	Management	Fragrance	Flavor	Aftertaste	Acidity	Body
Management	0.000						
Fragrance	0.168	-0.291					
Flavor	0.217	-0.279	0.578**				
Aftertaste	0.084	-0.236	0.482**	0.668**			
Acidity	0.471**	-0.198	0.315	0.532**	0.661**		
Body	0.394*	-0.152	0.504**	0.496**	0.526**	0.499**	
Balance	0.122	-0.596**	0.650**	0.793**	0.703**	0.536**	0.439**
Overall	0.263	-0.458*	0.698**	0.774**	0.657**	0.536**	0.673**

*. Correlation is significant at a 5% level (2-tailed). **. Correlation is significant at a 1% level (2-tailed).
Adapted from: [74].

Yadessa and his colleagues working with different shade trees, demonstrated that *Acacia abyssinica* and *Cordia africana* produced acidic coffee beans, with better flavor than those produced by *Albizia schimperiana* and *Albizia gummifera* [110]. In contrast, [6] reported that sensory characteristics were adversely affected by shade. They found that shade, at high altitudes, had an unfavorable effect on fragrance, acidity, body, sweetness, and preference of the beverage. These conflicting findings may be due to the different cultivars used in these studies showing that the use of shade, can lead to the production of high-quality coffee. All sensory variables were positively correlated with shade which suggested that the use of shade could improve beverage quality under all management levels.

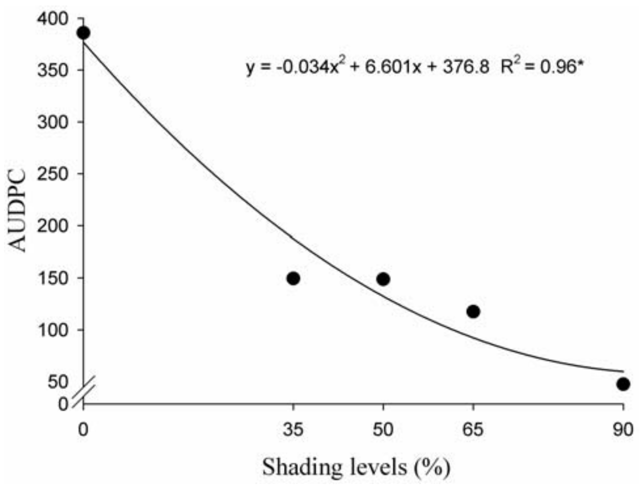
2.2. Diseases, Pests, and Weeds as Influenced by Shade

High yields went hand in hand with high incidences and low yields with low incidences. Coffee is vulnerable to several diseases and insect pests leading to losses in productivity and quality. Shading may change the environment for diseases and insect pests by modifying their microclimate through the moderation of wide fluctuations in air and soil temperatures and by increasing moisture. These changes likely explain why some diseases and pests are less successful under shade. The shade trees further enhance the variety of habitats for other organisms including pests, diseases, and their natural competitors [49, 94] noted that natural shade reduced weed incidences and species. He attributed this to the shading effects on C4 species and leaf fall which formed mulch and hence interfered with the growth of weeds.

Studies have been carried out to determine the influence of shade on coffee leaf rust show controversial results. In plots with dense shade, leaf rust incidence did not reach levels as high as in full sunlight. On the other hand, incidences of attack of coffee by coffee leaf rust (*Hemileia vastatrix*) are lower under shade [94]. These results suggest that shade has negative effects on leaf rust by keeping yields at low levels but favors leaf rust once production reaches a certain threshold, probably by favoring spore germination. This interpretation reconciles contrasting views on the effect of shade on coffee rust. Some authors have reported low attack intensities under shade, while others have reported a high rust incidence [89]. These different results could be explained by coffee tree yield and its interaction with shade. Although these measures were implemented to reduce coffee leaf disease, research has shown that disease dynamics depend on the specific disease, local fertilization conditions, humidity, elevation, temperature, and regional land management. This suggests that efforts to manage coffee leaf rust need to consider the type of shade that determines environmental and microclimatic conditions [4]. Highly diversified coffee systems will be better at reducing coffee leaf rust incidences in higher altitudes; whereas in lower altitudes less diversified agroforestry systems will be more suitable. This hypothesizes that the less diversified canopies maintain low moisture in lower altitudes, while in higher altitudes the highly diversified canopies maintain low temperature; both effects could reduce the development of the pathogen [17].

Vegetation complexity may increase coffee leaf spot (Mycena tricolor) [94], brown eyespot (Cercospora coffeicola), and coffee rust incidence, but with the latter two species, the specific cause of the increase is linked to humidity, not shade; rust incidence increases with humidity, independent of shade levels [89]. Other studies document no correlation between shade and leaf rust in Arabica varieties. Moderate shade (35%–65%) can reduce brown eyespot [94], weeds, and the citrus mealybug and can increase the effectiveness of parasites of other pests [53]. In addition, moderate shade levels can hinder fungal diseases by creating windbreaks and slowing the horizontal spread of coffee leaf rust spores [94]. Therefore, coffee disease cannot be reduced by shade management alone, but it can be in combination with modified humidity, predator management, and local and regional landscape management.

As reported by [5], for the area under the disease progress curve (AUDPC) lower cercosporiosis incidence was noticed in plants submitted to different shading levels (35, 50, 65, and 90%), confirming the supposed relationship that higher radiation levels increase the disease incidence (Figure 3). The treatment under full sun did not provide good coffee plant protection, obtaining the highest cercosporiosis incidence. These results corroborate those of [89], in which the authors verified that the cercosporiosis incidence was directly affected by the afforestation of the coffee plantation. The main causes of accentuated cercosporin are intensity is associated with the water deficit and unbalance or deficiency of some nutrients. Thus, the coffee plant under full sun would probably be more susceptible to the cercosporiosis incidence due to lower soil moisture, as a result of the direct exposure to the sun under this system. Higher soil moisture in the shaded system increases water and nutrient uptake over time, decreasing the cercosporiosis incidence in coffee plants [89].



Source: [5]

Figure 3. *Area under the disease progress curve (AUDPC) in the dry and rainy seasons for coffee plants, under different shading levels.*

Many organisms aid in pest control on shaded farms. Ants and spiders, for example, reduce the damage caused by the coffee berry borer, Hypothenemus hampei Ferrari, and the coffee leaf miner, Leucoptera coffeella Guer. Birds and bats predate arthropods in shaded coffee plantations. Predation services by birds [53] and bats [108] have been documented to improve coffee yields by 1%–14%. Shade provides an efficient biological management tool for the control of major pests like coffee white stem borer and thrips providing uniform shade is one of the major mechanisms for the effective management of the white stem borer and thrips which becoming very important pests, especially during prolonged dry season. Besides providing unfavorable conditions for this pest, the shade trees are also reported to harbor a variety of predatory birds and natural enemies of it, thus contributing towards natural and biological control of the pest [1].

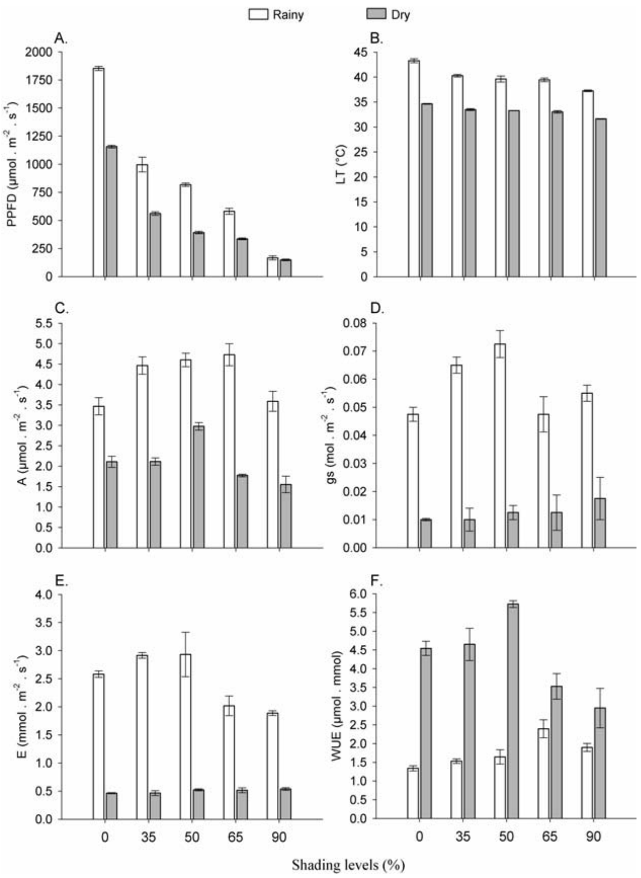
2.3. Effect of Agroforestry Systems on the Physiological Performance of Coffee

2.3.1. Shade Effects on Coffee Canopy Temperature Regulation

Temperature is one of the climatic factors which have a major impact on the physiology of coffee. Leaf temperature affects stomatal opening, transpiration, and photosynthesis [73]. The optimal air temperature range for Arabica coffee growth is 18-21℃ [38], and for its photosynthesis it is 18-24℃. For adequate root development, 24-27℃ seems to be the best soil temperature range. At air temperatures above 24℃, the net photosynthesis decreases, approaching zero at 34℃ [73, 63] observed deficient floral development and a large number of aborted flowers caused by high air temperatures (30℃ during the day, and 24℃ during the night). Increasing night-time temperature was the most significant climatic variable [22]; however, it can withstand temperatures of 15℃ during the night and 25 to 30℃ during the day. Exposure to temperatures of over 30℃ for extended periods could lead to stunted growth and abnormalities such as yellowing of leaves. High leaf temperatures may lead to excessive heat stress, moisture loss, and damage to plant cells. High temperatures during flowering, especially if combined with drought, may cause the abortion of flowers.

According to [74], leaf temperature was significantly affected by shade during the dry period but not during the rainy period and leaf temperatures tended to be lowest in the morning, peaking at midday then decreasing thereafter. Very high leaf temperatures of up to 38℃ were attained in full-sun coffee at midday in the dry period (Figure 4B). Leaf temperatures are generally higher than air temperatures since leaves are heated by absorbing solar radiation. Shaded coffee tended to have lower leaf temperatures than unshaded coffee during the dry period, with the difference ranging from an average of 1.2℃ to 1.93℃. [46] similarly observed that shade reduced temperatures in the coffee trees by up to 2℃. [5] found that leaf temperatures for both dry and rainy seasons were highest under full sun but declined with an increase in shading level (Figure 4B). Shade may limit or ameliorate the effects of hot dry conditions and limit moisture loss by moderating leaf temperatures. Shaded plantation systems can decrease extreme variations in leaf temperature and humidity within them [36]. An increase in shade cover could lead to a reduction in temperatures at the time of the day when plants are subjected to severe heat stress [57].

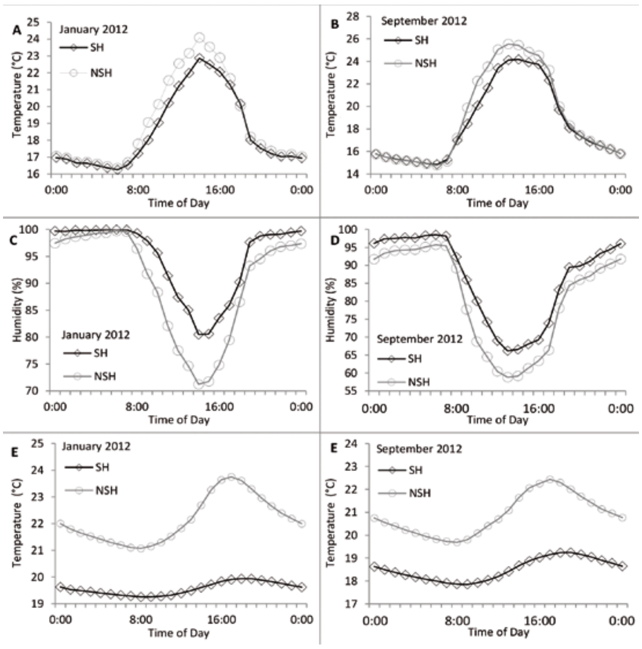
DaMatta and Ramalho observed differences in leaf temperature of 4℃ for inner leaves and 2℃ for outer leaves were reported between coffee trees grown in full sun and coffee trees grown in the shade [28]. Shade cover affects microclimatic fluctuations more dramatically than it affects mean values of climatic and soil moisture measurements [57]. Compared to coffee monoculture, coffee under shade trees, the maximum temperature of coffee leaves is reduced by up to 5℃ and the minimum air temperature at night is increased by up to 0.5℃, with these shade trees thus buffering against large diurnal variations in air temperature that are detrimental to coffee physiology [93].



Source: [5]

Figure 4. *Photosynthetically active photon flux density (PAPFD), leaf temperature (LT), photosynthesis (A), stomatal conductance (gs), transpiration (E), and water use efficiency (WUE) in the rainy and dry seasons for coffee plants, under different shading levels. Bars represent the standard error of the mean (n = 6).*

The protective effects of shading have been associated with the lower radiation input at the level of the coffee canopy, which may reduce the extent of photo-oxidative damages, a phenomenon frequently observed in coffee grown at full exposure in marginal zones, and ultimately increases crop life expectancy [28]. In addition, other major effects of shade trees on coffee physiology are associated with decreased wind speeds and temperature fluctuations (by as much as 4℃) (Figure 5A & B), increased air relative humidity (Figure 5C & D), and changes in aerodynamic roughness of the cropped area. Taken together, these alterations would decrease leaf-to-air vapor pressure deficit, which in turn would allow longer stomatal opening (thus favoring CO_2 uptake), without a proportional increase in transpiration rates. Hence, water loss due to excessive crop evapotranspiration should decline, an effect enhanced by increased ground cover and a decrease in the abundance of weeds [19].



Source: [19]

Figure 5*. Area averages of air temperature (A, B), air humidity (C, D), and soil temperature (E, F) by time of day, separated into wet (January 2012) and dry (September 2012) months. SH – shaded area, NSH – non-shaded area.*

Tree shades help to reduce the amount of heat reaching the coffee plant during the daytime (Figure 5A & B), and protect the coffee plants from the evening and night low temperatures as the trees will serve as a cover and protection, hence contributing to the creation of an ambient micro-climate, which suits well for the growth and development of coffee bush [1]. Generally, shade acts as a buffer to the coffee microclimate, since it towers over coffee. In the face of climate change and the resulting rainfall decline and increased fluctuations of temperature extremes, tree shade appears as an important climate adaptation coping strategy for smallholder farmers. These reduced fluctuations in microclimate variation with greater shade cover have the potential to keep coffee plants closer to their ideal temperature ranges preventing damage to the coffee plants from extreme minimum and maximum temperatures [57]. Shade could, thus, reduce the ecological and economic vulnerability of resource-poor smallholder farmers [26, 12].

2.3.2. Effect of Shade on Photosynthetically Active Radiation Reaching the Coffee Tree

According to [74], coffee in full sun recorded higher photosynthetically active radiation (PAR) reaching it than shaded coffee. This agrees with the findings by [5] who also observed a decrease in photosynthetically active photon flux density (PPFD) with an increase in the shading level due to the effect of tree leaves filtering out the red light and transmitting the green (Figure 4A). The PAR reaching coffee trees also increased with increasing distance from shade tree (reducing shade levels). The daily differences were more pronounced especially at midday, during the dry period, where the PAR recorded under coffee in full sun was much higher than that recorded under shaded coffee. During the rainy period, the daily trend in PAR was similar to that recorded in the dry period, however, the ranges tended to be higher in the late afternoon (Figure 4A). [68] demonstrated that shade causes a significant reduction in incident global solar radiation and PAR during the day. Shade has a direct impact on photosynthesis since it determines the amount of light that reaches the plants which in turn regulates their growth processes in reaction to changes in light intensity [106]. These results are in contrast with the findings by [5] who reported higher values in the rainy season than in the dry period. These conflicting findings may be due to the difference in methodology between the studies. For instance, [5] used plastic screens to provide different shading levels of 0 (full sun), 35, 50, 60, and 90%, whereas [16] used, natural shade trees. Factors such as shading type (natural or artificial), shading density, and species used can affect the outcomes of studies of this nature.

2.3.3. Effect of Shade on Photosynthetic Rates of Coffee

The photosynthetic rate is the rate at which CO_2 is assimilated to increase biomass [88]. According to these authors, high rates of photosynthesis mean that there is high biochemical and physiological potential for high carbon fixation capacity. However, different factors affect the photosynthetic rate of a given plant of which light intensity is one. Plants of the same species perform differently if they are grown under different light regimes [7, 8, 79] established that coffee underneath 50% shade had higher photosynthetic rates than plants under full sun in winter conditions. The rate of photosynthesis was higher in the dry season, in which the PAR was higher than in the rainy period. In contrast, [5] found a significant reduction in photosynthetic rates in the dry season (Figure 4C). Increase in photosynthetic rate under high radiation has been reported in several studies [37, 35, 3, 29, 19]. They attributed this to photo-inhibition during the cool, dry season and discrete, dynamic photo-inhibition during the warm, rainy season. [44] also revealed that chronic photo-inhibition can significantly decrease plant productivity. Stomata characteristically close early in the morning in coffee trees. Low stomatal conductance values have been recorded during the afternoon due to high stomatal sensitivity to an increase in vapor pressure deficit [88, 19]. The low stomatal conductance constrains the CO_2 influx into the leaves thereby reducing the rate of photosynthesis during the afternoon [28].

Cannell reported that the maximal photosynthetic rates of sun leaves of coffee are lower around 7 μmol CO_2 m^{-2} s^{-1} [15], but according to the work of [56] are higher for shade leaves up to 14 μmol CO_2 m^{-2} s^{-1} than for sunlit leaves. Similarly, [10] reported that Arabica coffee grown under full sunlight scored a lower rate of photosynthesis as compared to coffee plants grown under shade (50 and 70%). Bote and Struik discussed that Arabica coffee plants exposed to direct sunlight, increased air temperature which resulted in a subsequent lowering of stomatal conductance which in turn imposed a large limitation on the rate of CO_2 assimilation [8]. Kanechi, Kumar, Paiva and their colleagues pointed out that shade-grown plants photosynthesized at nearly twice the rate of those grown in the sun, with corresponding changes in leaf conductance. Since the stomatal aperture is greater under shade or on cloudy/rainy days [36], it may be suggested that under full sun photosynthesis would be largely restricted by low stomatal conductance [56, 51, 75].

There is also considerable information that contradicts the observations of [56, 15, 10, 41] observed in Arabica coffee a higher rate of photosynthesis in sun leaves from the upper canopy than in shade leaves from the middle canopy. Friend and Fahl also observed a higher photosynthetic rate in sun grown than shade-grown Arabica coffee plants [37, 35]. These results indicate that the photosynthetic rate of shade leaves was limited by the low light availability, rather than by stomatal conductance. Similarly, [106] pointed out that shade can result in net photosynthesis limitations due to insufficient light interception although, coffee leaves exhibit typical shade acclimation features, theoretically allowing them to maintain net photosynthesis in low light. Araujo and coworkers also reported that low physiological plasticity to low light in coffee leaves located inside the canopy resulted in reduced net photosynthesis as compared to exposed leaves [3]. The limitation of photosynthesis by low light availability has been proposed as one of the main reasons for lower yields of coffee grown in agroforestry systems in optimal coffee production areas and under high altitude coffee growing areas, shade provides little benefit to the crop [106]. These results may be due to the non-optimal shade regime in synchronizing with various climatic factors that may cause such contradictions. Generally, Shade makes the major difference in climatically marginal coffee production conditions, and higher levels of shade are needed with increasing temperature stress. Growing coffee under natural tree shade may be an important climate adaptation coping strategy for small-holder farmers, given that climate change is associated with rainfall decline and increased fluctuations of temperature extremes [31].

2.3.4. Effects of Shade on Stomatal Conductance of Coffee

Stomatal regulation is a key process in the physiology of *C. arabica*, as well as many other plant species, and hence it is a key parameter in many ecological models [8]. Stomatal conductance is intrinsically linked to photosynthesis and water relations, it provides insights into the plant's adaptive capacity, survival, and growth [23]. Stomatal movements can be affected by various environmental factors, including plant water status, CO_2 concentration, season, time of the day, and light. For example, bright light and low concentrations of CO_2 stimulate opening, while high CO_2 concentration even in bright light, causes closure. During the dry and rainy period, the stomatal conductance was higher in the morning decreased at midday, and was generally lower, with few exceptions, in the late afternoon. Similarly, Vaast also found higher stomatal conductance rates in the morning [99]. This means that various environmental and endogenous factors control stomatal movements, but light is of major importance. The stomatal limitations in coffee species are associated with a strong stomatal sensitivity to increasing leaf-to-air vapor pressure deficit (VPD) during the day [85, 99] and result in large reductions of photosynthesis, particularly in the afternoon [28]. For example, when coffee is grown in suboptimal (hotter and drier) growing conditions and full sun, the photosynthesis is lower than in the shade [52]; which has been related to the high sensitivity of coffee stomatal conductance to VPD [28].

Coffee leaves that were in permanent shade were reported to have had higher stomatal conductance rates than those that were exposed to full sun [107]. Other studies [99] have reported higher stomatal conductance rates in the morning and lower rates later in the day under shade. This has been attributed to high temperatures and vapor pressure deficit that induce stomatal closure. Baliza and coworkers reported that stomatal conductance was highest in coffee trees under 35 to 50% shade level [5] (Figure 4D). Between the seasons, for all treatments, a significant reduction of the photosynthetic rates were verified in the dry season, indicating that low night temperatures may largely depress in stomatal conductance, even when the daytime temperature is adequate for gas exchange in coffee plants [26]. In the rainy period, the 35 and 50% shading levels provided the highest stomatal conductance values, being superior to the other shading levels. These results corroborate those obtained by [16], who observed that the reduction of stomatal conductance values occurs starting from 50% shading. These results suggest that conductances are decreased under both extremes and intermediate shade levels are conducive for accelerated stomatal conductance rates. In addition, shade trees reduce wind speed and leaf temperature while increasing air humidity, and hence reduce VPD and the stomatal limitations of coffee photosynthesis; therefore, agroforestry production systems have been recommended for suboptimal growing conditions [99].

2.3.5. Effects of Shade on Water Use Efficiency and Transpiration

Coffee in unshaded plantations is normally more water-stressed than in shaded plants. In Central America, studies have shown that, where there was severe drought, the stress-alleviating effect of shade trees was more beneficial than the competition for water was detrimental [71, 102] found that trees in full sun tended to transpire more than those under shade trees, implying they faced a higher level of environmental stress. However, they also observed that the daily water usage was higher for coffee plants grown under shade, due to their greater vegetative growth than those in full sun. Furthermore, the water use by associated shade trees under these conditions did not affect soil water availability for coffee, although this may have been due to the high rainfall (over 3100 mm). There is, however, the possibility of competition for moisture particularly during the dry periods [102].

The presence of branches with higher leaf area during the cold and dry season at higher shade levels is a consequence of the greater leaf retention in these trees [13]. This can be due to the lower rate of soil moisture loss during the dry season as a consequence of the shading. In coffee trees, under conditions of agroforestry systems, a smaller transpiration rate per leaf unit than in unshaded trees has been reported [102]. Nevertheless, the same authors report a greater evapotranspiration in the agroforestry system due to the presence of trees. The lowest transpiration values in the rainy period were found in the highest shading levels (65 and 90%), an indication of higher environmental stress under non-shaded conditions, a fact already observed in coffee grown under *Cajanus cajan* L. shading [68]. There is also seasonal variation in transpiration and the lowest values of stomatal conductance, as well as of transpiration, were found in the dry season in comparison to the rainy season, without significant differences between the shading levels (Figure 4E).

Generally, shaded coffee had a higher transpiration rate than coffee in full sun except for the dry period [74]. The findings are comparable to those reported by [102] who showed that, while coffee transpired more per unit leaf area in full sun, the diurnal water intake per hectare was higher under shade. They further observed that the annual pooled water transpiration by coffee and associated shade trees ranged from 20 to 250% more than sole coffee grown in full sun. Results of this study show that shade had a significant effect on transpiration rate during the dry and rainy seasons. The low transpiration could be attributed to the fairly high leaf temperatures that were observed. As reported by [38], leaf temperature determines the vapor pressure deficit (VPD) within the leaf and is, therefore, the prime mover of transpiration. The results were supported by [42] who observed a strong and direct reaction of stomata to VPD. [99] found that coffee transpiration was restricted at higher VPD, recorded during the dry period, due to stomata closure.

Additionally, the presence of shade trees increases coffee plantation water use, but also decreases evaporation from the soil surface and increases rainfall infiltration in the soil (Figure 4F). Pollarding dates and intensities could be adjusted based on weather seasonal forecast to better deal with the contrasting effects of shade trees on coffee water supply. The lowest water use efficiency was found in the rainy period, with prominence for the 65% shading level about the other treatments. In the dry period, the highest value occurred at 50% shading, followed by the unshaded and 35% shading levels, while the lowest values were presented in higher shading levels, 65 and 90%. Similar results were found by [16], in which the efficient water use was higher in the plants under full sun and 50% shading, followed by 80% shading and shade-reduced PAR reaching the coffee tree, reduced leaf temperatures, and increased stomatal conductance and transpiration rates.

2.4. Agroforestry Systems and its Effects on Soil Characters

2.4.1. Effects of Shade on Soil Temperature

Soil temperature impacts the absorption of water and uptake of nutrients by plants, and also microbial activity that enhances organic matter content [80]. It plays a critical role in the survival of many organisms, but it varies in response to exchange processes that take place through the surface of the soil. Agroforestry with more shade has better moisture availability due to the lower rate of evapotranspiration from the coffee and soil layer [58]. The trees protect the coffee from direct sunlight and mulch the soil with their litter fall which also protects the soil from extreme temperatures and conserves soil moisture by decreasing the rate of evaporation [1]. The lowering of soil temperatures by shade when combined with the higher soil moisture would produce lower moisture stress on the shaded plants. The reduction in soil temperature, observed under shade, was mainly caused by the ability of shaded soil to stabilize the local thermal balances and also to reduce the heat flux caused by the accumulated plant-based biomass [68, 92] also reported that shading reduces and stabilizes the soil temperature by reducing the radiant flux reaching the soil and modifying the temperature amplitude at the soil surface.

On the other hand, the non-shaded area had higher soil temperature during the day and also during the night. Maximum ambient midday soil temperature at lower depth was lower in the shaded area (Figure 5E & F). Visible symptoms of damage to coffee can be caused by overheating. Although they found that the area without the protection of shade trees would get warmer, the differences in soil temperatures in shaded and non-shaded areas were small [68]. The reduced soil temperature registered for coffee grown under shade agreed with the result obtained by [13]. It can be concluded that the reduced soil temperature was mainly due to the reduced direct incidence of solar radiation on the soil surface. Shading buffers extreme temperature variations and provides a microclimate that attenuates extreme temperatures of air and soil and preserves surface soil humidity.

2.4.2. Effect of Shade Trees on Soil Fertility

In an agroforestry system, the shade canopy may enhance soil fertility by decreasing runoff, nutrient and fertilizer drainage, and soil erosion [97]. Though, its major benefit is the actual reduction in light transmission to coffee crops which softens the effect of biennial bearing and excessive vegetative growth [2, 27] showed that N input from shade tree litter fall alone was approximately 95 kg N ha^{-1} $year^{-1}$. There is a general understanding that the presence of trees positively influences soil nutrient content [50]. Trees can provide the soil with nutrients from their litter, primarily species that can fix nitrogen from the air. Shaded coffee agroecosystems reportedly have higher total C stock and higher total litter biomass than full sun or open systems [33]. Total carbon (C), due to its bearing on other physical, chemical, and biological indicators, is considered the key indicator of soil quality and agronomic sustainability [84, 78] reported that non-leguminous trees increased Ca, Mg, and K concentrations in the soil.

Agroforestry systems had better soil fertility than coffee in full sun, considering single effects of types of shade or in interaction with management intensity. Other studies have also documented the importance of shade for soil fertility in coffee agroecosystems. More trees mean less loss of nitrogen [97]. The use of bananas can help improve the cation exchange capacity [98]. In our study, shade was important for reducing acidity and increasing K independently of the other factors, and was capable of maintaining higher soil C and N levels with increasing management intensity (especially in CHD plots). The use of shade trees and bananas can reduce the need for nitrogen fertilizers and amendments for correcting the soil acidity, and thus, reduce both soil contamination and production costs. In addition, although soil physical indicators that are also important for soil fertility were not measured, it is known that soil C is closely related to organic matter and better soil physical conditions [95].

Physically, trees offer a network of fine and coarse roots that bind the soil thereby preventing erosion. The ability of many trees to utilize nutrient pools deeper in the soils, than crops would normally be able to access, leads to increased nutrient capture efficiency thereby reducing leaching losses to groundwater and environmental pollution [90]. Besides, the competition between shade trees and coffee roots for nutrients is considerably reduced since they utilize nutrients from different layers in the soil profile [90]. These nutrients are assimilated into the biomass of the trees and are returned to the soil surface over time through litter fall, decomposition, and mineralization processes thus making them available to the crops [72]. To reduce the possibility of competition between shade trees and coffee, particularly under low soil fertility, shade trees should be pruned regularly. This would lead to an increase in organic matter and nutrient return to the soil [33]. In Ethiopia, there are limited studies on the impact of shade trees on soil fertility under coffee cropping systems. Additionally, trees in coffee plots have been shown to retain more N in the ecosystem, thus decreasing N losses via leaching [97]. Additional N supply provided by litter decomposition and biological N fixation could help maintain the nutrient pool for coffee plants when economic conditions render the application of synthetic fertilizer too costly. It could be concluded from these experiments that, shade trees fix nitrogen, and that coffee plants absorb more of this additional source of N the closer they are to the tree. Additionally, trees in coffee plots have been shown to retain more N in the ecosystem, thus decreasing N losses via leaching [97].

2.4.3. Effect of Shade Trees on Soil Infiltration Rate

Higher infiltration rates are related to decreased runoff, as was shown by [14]. Regarding the measured soil litter and infiltration rate, [64] reported that, plots under Erythrina shade treatment performed better than full sun plots; the performance of these services in banana shade plots was too variable to conclude. Observation of higher infiltration rates in shaded plots, commonly associated with a less compacted soil structure, is consistent with the findings of [58]. This may support the hypothesis that this could lead to decreased erosion, in shaded plots. A study recently done on-site with field measurements of runoff and erosion is providing data that support this hypothesis: the sediment concentrations in runoff water seem to be almost constant throughout the year, allowing the Erythrina trees to decrease erosion [105]. Notably, improved water infiltration can help decrease the loss of topsoil by erosion; soil cover can help prevent water loss during the dry season [58].

Erosion is related to runoff, and increased soil cover can improve the structure of the upper soil layer, increasing the rate of water infiltration in the soil, and thus decreasing runoff, a regulating service [90]. A comparison of these variables in shaded and un-shaded areas of a coffee plantation would help ascertain the effects of trees on erosion and runoff. All these ecosystem services could contribute to improving the resilience and sustainability of the cropping system in the face of changing environmental and economic factors, even under intensive management.

2.5. Agroforestry Systems for Conservation of Biodiversity and the Provisioning of Ecosystem Services

2.5.1. Conservation of Biodiversity

Shaded coffee plantations are increasingly valued for their contributions to biodiversity conservation and the provisioning of ecosystem services. Since the 1990s, shade coffee has been noted for its contributions to conserving plant, arthropod, bird, bat, and nonvolant mammal diversity. More recent studies have documented patterns of bird, ant, and tree biodiversity declines, specifically in response to decreasing vegetation cover and increasing management intensity [77]. Biodiversity declines within coffee systems are of particular concern, given that ecosystem services such as pollination, pest control, erosion control, watershed management, and carbon sequestration are worth billions annually and are largely a function of biodiversity levels. Therefore, as a whole, ecosystem services tend to decline as forests are converted to shade coffee and as shade coffee is converted to low-shade coffee systems [32].

In Ethiopia, the aforementioned coffee production systems represent a gradient from the most traditional and structurally diverse systems (forest coffee) to the least diverse system (plantation). The coffee forests are the most diverse and relatively intact remnant natural habitat of the Afromontane biodiversity hotspot occurring in Ethiopia. They are rich in regional endemic species. Besides, they are also habitats for economically important crop genetic resources, like Arabica coffee, and spices like *Aframomum corrorima* and *Piper capense*. Ethiopia is believed to possess about 99.8% of the total Arabica coffee genetic diversity [55]. These diverse genetic resources are vital in selecting coffee varieties that are of high quality, resistant to diseases/insect pests, and adapt to climate extremes (drought/ temperature).

The effectiveness of different types of shade to provide major ecosystem services in coffee plantations depends both on the altitude where the coffee is grown and how the system is managed. A study by [17] revealed that no trade-offs were found between different ecosystem services, and between ecosystem services and biodiversity. This indicates that it is possible to increase the provision of ecosystem services without decreasing the provision of other ecosystem services. More ecosystem services are provided by coffee agroforestry systems than by coffee systems in full sun. Coffee agroforestry systems should be designed with diverse, productive shade canopies and managed with a medium intensity of cropping practices, to ensure the continued provision of multiple ecosystem services. Cognizant of the importance of coffee forests for the conservation of biodiversity at ecosystem, species, and genetic diversity levels, researchers have long advocated the establishment of *in situ* conservation areas [39, 91]. Based on these research findings and the transition of the country's development strategy from food security and poverty reduction to an integrated, sustainable development path, the government of Ethiopia established new conservation areas in the southwest part, rich in coffee forests. Therefore, smallholder farmers should be able to design and manage shade trees without undermining their productive and economic objectives, and at the same time ensure the delivery of other ecosystem services.

2.5.2. Coffee Agroforestry as Resilience and Mitigation to Climate Change

Climatological models predict that the Caribbean and Central America will experience general drying as well as stronger later-season hurricanes. Hurricanes can result in major economic losses for coffee farmers, but farms with more complex vegetation (i.e., greater tree density and tree species richness) experience significantly fewer posthurricane landslides [77]. Coffee farmers, realizing the enhanced risk in less-shaded fields, have engaged in posthurricane mitigation focused on increasing the planting of more shade trees within their coffee fields. In Ethiopia, a recent climate change impact prediction on indigenous Arabica coffee [31] showed a profoundly negative trend for future distribution under the influence of accelerated global climate change. Accordingly, the current predicted areas of distribution of indigenous Arabica coffee in Ethiopia can be reduced by 38% in the most favorable scenario, and by 90% in the least favorable scenario, by 2080. This would place populations in peril, leading to severe stress and a high risk of extinction. Shade modifies the micro-climate, and can moderate extreme temperature by at least 5^0C. Shaded systems have also been identified as part of the remedy for confronting harsh new environments in coffee regions that result from climate change [28].

Coffee plants are highly adapted to the climate patterns of the tropics but are sensitive to changes in weather conditions [16]. Although coffee requires a defined period of drought, extended water stress damages the plant. Crop yields in rain-fed systems may decrease by 40–80% during drier El Nin˜o years [26]. Human-induced land-use change is one of the major sources of greenhouse gas (GHG) emissions, resulting in climate change. Maintaining the high canopy cover of traditional coffee production systems contributes to a reduction in deforestation, and hence reduction in GHG emissions. Further, increasing the shade tree component in relatively open coffee production systems like home gardens in eastern Ethiopia can make the system climate-smart, and help in sequestering carbon from the atmosphere, while also making the production system resilient to the effects of climate change. The GHG emissions are reduced through avoided deforestation and also sequestered through enhancement of degraded forest share generating emission reduction (ER) credits that can be traded through emerging REDD+ climate finance architecture, and generate additional finance for sustainable forest management and agriculture [65]. In summary, overall, agroforestry systems have proven to be more effective than full-sun coffee for the provision of ecosystem services, and consequently for improving farmers´ livelihoods. Furthermore, the delivery of multiple ecosystem services can considerably increase the economic value of the land [25, 76], which is important for both current and future generations.

3. Modeling Agroforestry

Although previous research on coffee agroforestry systems has identified these beneficial effects and various other environmental factors that affect growth and yield, our quantitative knowledge of coffee agroforestry systems is still limited. [82] described the agroforestry literature as ‘‘plagued with generalizations that have not been critically substantiated with scientific data''. Research has mostly been carried out on a small number of sites, often near research institutes. Experimental treatments in coffee systems have mainly focused on management options, like fertilization level or choice of shade tree species. This has left little room for comparative study of the effects of differences in weather or soil characteristics. Due to the long periods involved in tree growth, our understanding of agroforestry systems will be very restricted if it only depended on experimental data. One way to improve our understanding and management of agroforestry systems and integrate the scattered knowledge on coffee agroforestry is by using a process-based model. The key role of crop models is to help understand and predict the links between crop development and climate, soil, management, facilitation, and competition between species. Crop models can provide insights into the main emerging agricultural challenges such as food security, sustainability, how to enhance ecosystem services, and how to cope with the possible negative effects of climate change [62]. There is an increasing need to address these issues at a global scale to identify the different solutions available [61], especially when products are exchanged on the global market, like coffee.

This approach rests on the idea that the productivity of coffee and associated trees may be site-specific, but the underlying mechanisms and processes operate generally. The models link physiological processes and morphological structures to predict biomass production under varying environmental factors. However, for modeling data on parameters and environmental drivers need to be available. If the data are incomplete, the modeling cannot be applied, or only with a large degree of uncertainty on its outputs. Perennial plantations are difficult to study because their relatively long growing cycle extends the period necessary for data acquisition, and because the heterogeneity of the canopy sometimes significantly increases the intra-plot light and micro-meteorological anisotropy, such as for temperature, vapor pressure, or aerodynamic conditions [59, 60]. Agroforestry systems (AFS) are probably the most complex perennial agroecosystems, because they have the most heterogeneous vertical and/or horizontal canopies, and these affect all ecosystem fluxes [104]. Yet, AFS have the potential to enhance ecosystem services [50, 58] such as carbon sequestration; and to mitigate climate pressure on crops [57].

Models have also already been developed to simulate coffee, grown in full sun or agroforestry systems:

Rodr ǵuez and colleagues proposed a model to simulate coffee in monoculture only, from branch to whole-plant scales. The model was calibrated from planting to five years old. The strength of this model lies in the fine phenology and physiological processes of the modeled coffee plant using branch-level cohorts of flowers and fruits over the entire two-year reproductive cycle. Indeed, cohorts are required to realistically distribute the demand for carbon of the fruits over the course of the season, and not all at once [86]. This model was successfully used for Colombian and Brazilian sites, two regions with contrasting climates and flower phenology (subtropical and equatorial). However, this model was not designed for large plots, long rotations, or agroforestry: coffee light absorption is computed using the Beer-Lambert law using a constant coefficient of extinction, absorbed light is converted into photosynthesis using constant light use efficiency, and coffee pruning, shade trees, canopy temperature, water and energy balance are not implemented in the model.

Another model was developed by [103]. This is a 1D-plant average plot-scale model for coffee grown in agroforestry systems, simplifying the intra-plot microclimate into either below shade or in full sun. One clear advantage of this model is the number of modules it includes to compute several ecosystem services and to incorporate various types of shade tree management and species, and the thorough Bayesian parameterization approach that was used. The model is simple, fast, and can be run under changing climates. It was recently applied in East Africa under climate change scenarios by [81]. The main limitations of the model are (i) its light transmission module does not consider light distribution as a continuum under shade trees, as described in [18], (ii) its formalism of LUE which is not influenced by the shade management even though found it to be greatly impacted, (iii) its lacks of a reserve compartment and of a cohort module and again (iv) the absence of energy balance and temperature of the canopy to drive the reproductive development.

Two other models have also been applied to coffee in an agroforestry system using 3D light interception modules: in [30], where only a sample of a few coffee plants were simulated, and using the MAESPA model to simulate the whole system. Since MAESPA was recently demonstrated to accurately predict light distribution, canopy temperature, and water and energy balance in such systems [18, 104], the model can readily compute all variables that are potentially influenced by the complex canopy structure. However, its relatively high computation time still limits its application for full rotations of coffee under AFS.

DynACof (which stands for Dyn*amic* A*groforestry* Cof*fee crop model*), is a daily plot scale crop model [69] with two layers of vegetation (shade trees and coffee plants) and three soil layers, aimed at simulating the growth and yield of coffee plantations under various shade tree species and management options, considering the spatial heterogeneity of the shade tree canopy. The coffee layer can be simulated either in monoculture or in agroforestry systems. Each layer is simulated sequentially at a daily time step. Spatially dependent variables, i.e. light absorption, LUE, transpiration, plant sensible heat flux, leaf water potential, and soil net radiation are all computed using metamodels from MAESPA. The model accounts for potential competition for light acquisition and water availability between plant layers. Nutrients and water are considered non-limiting in the first version, which is realistic for many field conditions in Costa

Rica. Water competition is simulated virtually from the day-to-day fluctuations in water content in each shared soil layer that can be reduced by drainage and evapotranspiration, or increased by precipitation. This simple formalism was found largely sufficient given the absence of water limitations in the application concerned [104], but can also reproduce the competition between plants under more constrained conditions.

It is argued that a proper combination of the inherent strengths of the above-described models could provide significant improvements and extend application domains. Metamodels are generally used to better understand the processes at stake in a model and to assess model sensitivity and uncertainty [20], for optimization [83], or to make faster and reasonably accurate predictions for a given variable that is usually computed by a time-consuming model, but with fewer simulation errors compared to simpler models [62]. Metamodels are often used as an efficient and simple tool to combine models at different time and/or space scales without running the finer-scale model iteratively.

Consequently, DynACof was designed to incorporate a plant-scale reproductive phenology formalism inspired by [86] but dependent on canopy temperature, with different sub-modules to adapt coffee and shade tree management, density and tree species, as in [103], and metamodels calibrated from MAESPA simulations for spatially-dependent variables, such as diffuse and direct light extinction coefficients, light use efficiency, leaf water potential, transpiration, and sensible fluxes [104].

This literature review revealed knowledge gaps for the different parts of coffee agroforestry systems: coffee plants, trees, soil, and weather. For various parameters, no or only a few values have been reported, and for none of the parameters, systematic studies of genotype–environment interaction were found. With a view toward model development, the following measurements and measurement programs may address the key knowledge gaps:

1. More and longer time series of daily weather data in different coffee-growing regions.
2. More long-term experiments that follow seasonal and inter-annual changes in coffee and trees, rather than one-off observations.
3. Data from multi-factorial experiments. Of particular value would be a systematic comparison of the same major shade-tree species, planted on a range of sites across different coffee growing regions differing in soil and climate, with additional differences in management.
4. Measurements on the impact of pruning on tree morphology.
5. Soil measurements that extend to greater depths than the top 10 or 20 cm.
6. Closed-balance studies for carbon, nitrogen, and water which allow quantification of the full flux budgets without the need for guesses regarding missing fluxes.

It would be useful if these proposed measurement activities were carried out in a regional network, using standardized protocols. This would help determine to what extent the large differences between reported values are due to differences in methodology or to true genotype–environment interaction. The spatial distribution would also provide a more robust basis for process-based modeling aimed at explaining and predicting coffee agroforestry system performance across the different coffee-growing regions.

4. Summary and Conclusion

This review of the literature reveals that agroforestry systems have the potential to alleviate adverse weather conditions, thereby providing a suitable microclimate for coffee production. Different studies have shown that shade cover affects fluctuations more dramatically than the mean values of climatic and soil moisture measurements. It can provide several important benefits to coffee plants by reducing air and soil temperature extremes, reducing high wind speeds, and improving and maintaining soil fertility by returning large amounts of leaf litter to the soil underneath. It also softens the effects of the biennial bearings. In contrast, shade trees may decrease the incidence of some commercially important pests such as coffee trips, coffee stem borers, coffee leaf miners, and coffee leaf rust. Although coffee can be grown without shade at optimal sites using high agrochemical inputs, at the expense of environmental degradation, in the face of climate change and the resulting rainfall decline and increased fluctuations in temperature extremes, tree shade appears to be an important climate adaptation coping strategy for smallholder farmers. Shade trees have a positive effect on coffee yield and quality even under optimal conditions. Therefore, it is necessary to promote smallholder farmers growing coffee under shade and to be able to design and manage shade trees without undermining their productive and economic objectives, while simultaneously ensuring the delivery of other ecosystem services.

The overall interactions between coffee and shade regimes are dependent on the climate, soil conditions, and management intensity. When designing new coffee systems, farmers need to consider the types of shade that adapt to the climate conditions and altitude at which the plantation occurs, types of soil with different characteristics, and management practices that aim to control soil fertility. It is also important to integrate fruit plants such as bananas and productive tree species (timber trees) to ensure additional income for farmer households as well as provide other services (e.g., shade, protection, N fixation). Extension services should support farmers with the choice of shade tree species and improve tree management, considering local market prices of timber and fruits. Such extension services seem to be increasingly important in response to fluctuating coffee prices, rising production costs, and reducing the ecological and economic vulnerability of resource-poor smallholder farmers. Agricultural extension and training of farmers, as well as adequate certifications, market-based incentives, and payment of ecosystem services, can help promote the adoption of well-designed, sustainable coffee agroforestry systems that provide both economic and ecological benefits.

Increased knowledge of the ecophysiological determinants of yield is a fundamental requisite for the development of models addressing high cropping efficiency in addition to establishing guidelines for introducing better farming practices for the enhancement of coffee productivity. The development of a model for coffee agroforestry systems aimed at exploring the systems' response to strategic management decisions (fertilization level, shade-tree species, and density, pruning, and thinning regimes), regional differences in growing conditions (weather and soil) and environmental change (climate and atmospheric composition). The purpose of modeling managed ecosystems is typically twofold. First, the process of model building and parameterization highlights gaps in our knowledge, which may help in setting the research agenda. Secondly, the completed model may be used to explore how different factors, under human control or not, affect the productivity and environmental impact of the system. Therefore, Process-based modeling might benefit the development of coffee agroforestry systems.

Developing an understanding of the factors that determine crop yield is essential for creating models that promote high-efficiency farming practices and establish guidelines for improving coffee productivity. To achieve this, it is necessary to develop a model for coffee agroforestry systems that evaluates the effects of various management decisions, such as fertilization level, shade-tree species, and density, pruning, and thinning regimes, as well as regional differences in growing conditions, including weather and soil, and environmental changes, such as climate and atmospheric composition. The purpose of modeling managed ecosystems is twofold. First, the process of model building and parameterization can help identify areas where more research is needed, which can inform future research priorities. Secondly, the completed model can be used to explore how various factors, whether under human control or not, affect the productivity and environmental impact of the system. Therefore, process-based modeling can be beneficial for the development of coffee agroforestry systems.

5. Prospects

Undertaking extensive physiological research within the realm of agroecosystems to delve into the influence of environmental factors, such as light, temperature, CO_2, nutrients, and water availability, on the productivity of coffee plants is an area of great potential. Particular emphasis should be placed on the investigation of shade's impact using a diverse range of tree species and coffee varieties across diverse geographical locations. Furthermore, it is of paramount importance to conduct studies to comprehend the influence of shade on soil moisture dynamics.

Research should be conducted to investigate the impact of shade on microclimate, coffee physiology, productivity, and quality so that appropriate recommendations can be provided to extension services and coffee farmers regarding the selection and management of shade tree species in different ecological zones. Additionally, to balance economic and ecological objectives in coffee systems, extensive economic analyses are necessary to make generalizable conclusions and gain insight into the trade-offs between economic and environmental performance.

Abbreviations

AFS	Agroforestry Systems
GHG	Greenhouse Gas
ICO	International Coffee Organization
PAR	Photosynthetically Active Radiation
PPFD	Photosynthetically Active Photon Flux Density
VPD	Vapor Pressure Deficit

Authors Contributions

Kalifa Nasiro is the sole author. The author read and approved the final manuscript.

Conflicts of Interest

The author declares no conflicts of interest.

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