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Coffee carbon stocks, pest and diseases under varied shade management: A review

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Coffee carbon stocks, pest and diseases under varied shade management: a review

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the Faculty of the Undergraduate
College of Science and Mathematics
James Madison University

by Anna Elizabeth Nordseth

May 2017

Accepted by the faculty of the Department of Biology, James Madison University, in partial fulfillment of the requirements for the Honors College.

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Abstract

Coffee agroforestry systems have received increased attention in recent decades because of their capacity to improve agricultural sustainability. Coffee (Coffea arabica), one of the most economically important crops, is widespread throughout the tropics and can have serious environmental impacts. To ensure sustainable coffee production, it is critical that coffee systems are maintained to maximize carbon storage and minimize susceptibility to pests and diseases. This study reviews the history of coffee production, from forested coffee systems to industrial coffee monocultures. We describe the five classifications for coffee systems, and use them as a framework to compare aboveground carbon stocks across management regimes and site conditions with a specific focus on coffee tree carbon stocks. Finally, we synthesize literature on coffee pests and diseases under varied shade management and investigate how these relationships may be altered with future climate change. Although no direct relationship was found between levels of shade management and coffee carbon stocks, site conditions such as precipitation and temperature appear to influence coffee carbon stocks depending on whether the coffee is grown in sun or shade. Additionally, the relationship between shade management and the prevalence of pests and diseases was unclear. Increasing our understanding of how site conditions and system shade management affect coffee carbon stocks and the prevalence of pests and diseases will allow for improved land-use planning, greater resiliency of coffee systems, and increased potential for agroforests to play a role in climate mitigation.
1 Introduction

Agroforestry systems have received increased attention in recent decades because of their contribution to sustainable agricultural production (Nair 2009; Jose 2009). Of particular interest is the role that agroforests can play in mitigating climate change through the sequestration of atmospheric carbon into long-term carbon (C) stocks (Schroeder 1994; Nair et al. 2009). There is abundant literature exploring the effects of different shade management practices on coffee system C stocks both above and below ground (Ávila et al. 2001; Noordwijk et al. 2002; Dossa et al. 2007; Soto-Pinto et al. 2010; Schmitt-Harsh 2012; Hager 2012; Souza et al. 2012; Noponen et al. 2013; Richards and Mendez 2014; van Rikxoort et al. 2014; Ehrenbergerova et al. 2015; Tumwebaze and Byakagaba 2016). However, to fully understand C stocks in agroforestry systems, it is important to know how individual components of a coffee system (e.g. coffee trees) contribute to C stocks and how these C pools are affected by system management and site conditions. Enhancing our understanding of how site conditions and system shade management affect coffee C stocks will allow for improved land-use planning and increase the potential for agroforestry to play a role in climate mitigation.

In this review, we summarize the history of coffee production from predominantly forested coffee systems to more industrial coffee monocultures. We then describe the widely accepted classifications for coffee systems today, and use them as a framework to compare aboveground carbon stocks across management regimes and site conditions from 14 studies with a specific focus on coffee tree carbon stocks in seven of those studies. Finally, we synthesize literature on coffee pests and diseases under varied shade management and how these relationships may be altered with future climate change. We recognize that coffee systems are vulnerable to climate change and can play an important role in climate mitigation.
1.1 Global importance of coffee

Coffee is one of the most important agricultural commodities in the world with respect to global trade (Varangis 2003; Aksoy and Beghin 2004; Daviron and Stefano 2005). In 2003, the export retail value of coffee reached over $70 billion (Vega et al. 2003), making coffee production the economic backbone of many developing countries (Varangis 2003; Jaramillo et al 2009; van Rikxoort et al. 2014). In Uganda, for instance, coffee exports account for 20-30% of foreign exchange earnings (Jassogne et al. 2013). More than 25 million people on over 5 million farms worldwide depend on coffee cultivation as their primary source of income (Fitter 2001; Pendergrast 2010). In Latin America, some 700,000 people grow coffee—a figure that does not include workers further down the production chain (Rice and Ward 1997). Therefore, any reductions in coffee production can be devastating to the economies of developing countries and leave coffee producers without a stable source of income.

Agriculture is a dominant land use in the tropics land and is one of the leading causes of tropical deforestation (Grau and Mitchell 2008). It is estimated that 10-12% of anthropogenic greenhouse gas (GHG) emissions are produced by agricultural activities, a number that is expected to grow with continued land transformation (Smith et al. 2007). Given its global prominence, coffee cultivation has a profound environmental impact, especially with respect to GHG emissions (van Noordwijk et al. 2002; van Rikxoort et al. 2014). There are two possible areas for reducing coffee GHG emissions: the carbon footprint of coffee production (e.g. fertilizer and pesticide inputs) and the maintenance of existing C stocks through diverse system management (van Rikxoort et al. 2014). Coffee systems cover over 11 million hectares throughout 60 countries in the tropics and subtropics (Waller et al. 2007). These coffee agroecosystems have replaced areas of productive and biodiverse tropical forests (Waller et al
2007). Land conversion for coffee production often occurs in phases where first the understory is cleared for traditional systems, then gradually intensified over time. Alternatively, coffee systems can be established on land previously cleared for cattle ranching or another agricultural exploits. Regardless of their origin, coffee systems now have the potential to serve as important connectors between remaining tropical forest patches (Klein 2002). Furthermore, the land under coffee cultivation continues to grow as global demand for coffee increases, necessitating more land for cultivation and better growing methods to improve yields (Hylander et al. 2013).

1.2 Ecology

Of the many species in the Coffea genus, Coffea arabica (Arabica coffee) is the most widely cultivated, accounting for over 70% of coffee production worldwide (Waller et al. 2007). Arabica coffee evolved as an understory shrub in the highlands of Ethiopia between 1500 and 2800 m asl (DaMatta 2004). Today, coffee production has spread around the world and can be found in countries throughout the tropics and subtropics, forming a zone known as the ‘coffee belt’ (figure 1).

Figure 1. Map of the coffee belt. Shades of brown represent area under cultivation with darker colors representing more area. Pie charts depict estimates of shade production within each coffee region. Image from FAO (2010).
Optimal coffee growing sites are reported between 1200 and 2100 m asl (Vaast 2008). Elevation \textit{per se} does not affect coffee growth but other critical climatic factors closely associated with elevation, particularly temperature and rainfall, are important determinants of coffee crop success (DaMatta 2004). Due to a high global market demand, in addition to other factors, coffee is often grown outside optimal growing areas under suboptimal conditions (Muschler 2001; Schaller et al. 2003; Vaast et al. 2008). Coffee can tolerate temperatures as high as 30° C and as low as 18° C, but these temperature extremes can cause significant declines in yields (Camargo 1985). In addition, suboptimal coffee zones may have poor soil, insufficient rainfall, or high winds which can lower coffee productivity, and quality (Beer 1987; Beet et al. 1998; Pendergrast 2010).

1.3 Coffee and climate

Coffee is a climate-sensitive crop and projected changes in global temperature and rainfall patterns could have dramatic impacts on productivity and distribution (DaMatta 2004; Jassogne 2013; Haggar and Schepp 2011; Davis et al. 2012; Fournier and Stefano 2004; Camargo 2010). For example, prolonged exposure to elevated temperatures can slow growth and lead to developmental abnormalities (Franco 1958), and high temperatures during flowering, especially in conjunction with drier conditions, leads to flower loss and ultimately reduces yields (Camargo 1985). Some models have shown that, under climate change scenarios predicted for 2020, current coffee production may be reduced by up to 34%. Such losses in production would inevitably have a major impact on economies in major coffee producing countries.

Despite climate volatility and its potential impacts on coffee yields, coffee systems can play a major role in mitigating climate change. Coffee is traditionally grown under the forest
canopy and, unlike many sun-loving crops, can thrive in low-light conditions. Though management and production intensities vary considerable, as will be discussed in section 1.4, the capacity of coffee systems to sequester and store C is high (Nair et al. 2009). Therefore, increasing C stocks through diversified agricultural systems may be a critical aspect to future climate mitigation.

1.4 Coffee System Management

Until the latter half of the 20th century, the majority of coffee production took place under complex, shaded small-holder systems where little or no land clearing was done and coffee trees were incorporated into the existing forest. This began to rapidly change in the 1970s with the devastating spread of coffee leaf rust (*Hemileia vastarix* Berk.) throughout Latin America, destroying coffee crops throughout the region. The response to widespread blight was to modernize or ‘technify’ of plantations by removing shade trees to help reduce moisture levels, thereby preventing the spread of leaf rust (Jha 2011). An additional perceived benefit of technification was the ability to greatly increase planting densities, thereby increasing yields (Hudson and Hudson 2004; Jha 2011). In the Chiapas region of Mexico, removal of shade allowed producers to plant up to three times more coffee trees in the same areas (Hudson and Hudson 2004). The modernization of coffee systems was supported largely by government agricultural policies (Hudson and Hudson 2004; Jha 2011). By 1996, about 40% of coffee farms in Latin America had been transformed from traditional, species diverse systems, to low shade systems or “sun-grown” coffee (Rice and Ward 1996). Some of the most dramatic intensification took place in Colombia, where shade trees, most of which were remnants of the original forest, were preemptively removed from coffee plantations to prevent leaf rust outbreaks (Guhl 2004).
By the early 1990s, 30-40% of coffee systems in Central America had been converted to coffee monocultures with either highly manicured, single-species shade trees or no shade at all (Rice and Ward 1999). However, nearly in sync with coffee system modernization came a surge of research into the effects of shade removal on ecosystem services such as the maintenance of biodiversity and carbon sequestration (Herzog 1994; Muschler 2001). Additionally, the planting of economically beneficial shade trees is a boon to farmers because it provides an alternative source of income in the case of fluctuations in the coffee market (Bellow et al. 1999).

Modern coffee systems are greatly varied in terms of vertical complexity, species richness, and other management practices (Figure 2: Moguel and Toledo 1999; De Beenhouwer 2016). Coffee producers select a system based on desired outcomes, which often require tradeoffs between yields, coffee quality, and ecosystem services (Bellow et al. 1999; Siles et al. 2009). Production systems fall into two major categories, shaded and unshaded, which have been shown in some instances to affect microclimatic conditions enough to alter coffee yields (Siles et al. 2009). When incorporated, shade trees are selected based on structural qualities (e.g. crown structure and root characteristics) (Schroth 1995; Vaast 2005).
as well as functional qualities (e.g. nitrogen fixation, food, or timber) (Bellow 1999; Starver 2001). Functionally beneficial shade trees can help coffee growers by increasing soil fertility, decreasing the need for agrochemical inputs, or by providing products that can be sold for additional revenue (Vaast et al. 2008; Siles et al. 2009).

Moguel and Toledo (1999) identified five major categories of coffee systems that can be found throughout the coffee belt: traditional rustic, traditional polyculture, commercial polyculture, shaded monoculture, and unshaded monoculture (Figure 1). The first four categories are agroforestry systems as they contain two biologically interacting species, one of which is a woody perennial (Somarriba 1992). Traditional rustic systems most closely resemble natural forests (Figure 3). Here, only the understory has been replaced with coffee shrubs leading to low density coffee plantings. These systems have high shade density ranging from 71-100% and a canopy height of 30-40 m (Table 1). Traditional rustic systems are the least intensively managed and, consequentially have relatively low coffee yields. For example, Peeters et al. (2003) recorded mean coffee yields of 573.0 ± 122.5 kg ha⁻¹ in a traditional rustic system in Mexico. Traditional polyculture systems couple intense understory manipulation with natural overstory vegetation (Figure 3; Figure 3. Five major categories of coffee system management and their associated structural complexity. From Moguel and Toledo 1999.)
Table 1). The result is a high-density production area or “coffee garden” with between 41-70% shade cover (Table 1). Coffee yields in traditional polycultures have been reported around 962 ± 321 kg ha\(^{-1}\) (van Rikxoort et al. 2014). Commercial polyculture systems contain little or no original forest vegetation (Figure 3). Instead, select overstory trees (typically saplings) are planted at the time of plantation establishment to serve the dual function of shade provision and economic utility. Coffee is planted at a low density with yields around 1,763 ± 931 kg ha\(^{-1}\) (van Rikxoort et al. 2014). Shade trees in commercial polycultures can either be native or exotic and often include a combination of timber, leguminous (for N-fixation), food, and other commercially important species (Gobbi 2000).

Modern coffee systems are comprised of shaded monocultures and unshaded monocultures. These two types of coffee systems have the highest yields, require the most intensive management, and receive the greatest amounts of agrochemical inputs. Shaded monocultures, sometimes referred to as ‘technified shade systems’ (Gobbi 2000), typically have a sparse canopy, made up of one or two economically beneficial species. Unshaded monocultures completely lack canopy cover, allowing coffee plants to be exposed to full incoming solar radiation. Shaded and unshaded monocultures are highly productive systems with coffee yields of 1,235 ± 550 kg ha\(^{-1}\) and 2,387 ± 1,240 kg ha\(^{-1}\) respectively (van Rikxoort et al. 2014).

Table 1. General attributes of coffee systems based on management style. Adapted from van Rikxoort et al. (2014) and Perfecto et al. (2005).

<table>
<thead>
<tr>
<th>System</th>
<th>Shade tree density</th>
<th>Percent shade cover</th>
<th>Canopy height (m)</th>
<th>Density of co-products</th>
<th>Input level (plant density, fertilizer, and pesticide use)</th>
<th>Yields</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional rustic</td>
<td>Very high</td>
<td>71-100</td>
<td>30-40</td>
<td>Low-medium</td>
<td>Very low</td>
<td>Very low</td>
</tr>
<tr>
<td>Traditional polyculture</td>
<td>Very high</td>
<td>41-70</td>
<td>20-30</td>
<td>Medium</td>
<td>Very low</td>
<td>Very low</td>
</tr>
</tbody>
</table>
While these five categories greatly simplify the gradients of complexity in coffee production systems, they serve as an important framework under which we can compare coffee systems. All four shaded systems can provide economic and environmental benefits in addition to the primary objective of coffee production; however, with these benefits there are often trade-offs such as lower total yields, higher pest susceptibility, and greater labor input. For example, the incorporation of shade trees at a suboptimal, low elevation site in Costa Rica reduced coffee yields by as much as 30% compared to a coffee monoculture at the same site (Siles et al. 2010).

### 2 Carbon Stocks

Agroforestry has long been promoted as a more sustainable form of agriculture, in part, because of the capacity of agroforests to meet human needs while simultaneously mitigating climate change through carbon (C) sequestration (Palm et al. 2004; Nair et al. 2009). Carbon is sequestered as gaseous C is removed from the atmosphere and stored in a long-term reservoir in the environment (*i.e.* C stocks). By incorporating trees into the agricultural landscape, there is more biomass than with crops alone, resulting in larger C stocks.

#### 2.1 Above- and Belowground C

Aboveground carbon (AGC) is stored in plant biomass, which can take the form of planted trees, naturally regenerating understory vegetation, leaf litter, and snags (Nair 1993; Nair 2009). When original forest vegetation is removed, AGC stocks are greatly reduced (Sitompul et
al. 2001). For example, in Indonesia, conversion of a rainforest to a cacao agroforest reduced plant biomass and C stocks by an average of 75% (Steffan-Dewenter et al. 2007). However, establishing agroforestry systems on previously cleared land, such as abandoned cropland or cattle pasture, can recapture 5-60 Mg ha$^{-1}$ of atmospheric C (Sitompul et al. 2001; Nair 2009; Soto-Pinto et al. 2010).

Belowground carbon (BGC) includes root systems, soil microorganisms, and inorganic C (Raich and Nadelhoffer 1989; Nair 2009). Unlike with AGB, forest clearing does not necessarily reduce BGC (Post and Kwon 2000). In fact, well managed pasture systems have been found have nearly equivalent BGC stocks to forests (Franzluebbers et al. 2000). BGC can comprise a substantial portion of total C stocks in coffee agroforestry systems; however due to difficulties in accurately measuring BGC, it can be impractical to compare BGC measurements between sites (Sanderman and Baldock 2010).

2.2 Coffee C Stocks

Numerous studies have examined the relationship between the coffee shade management and total C stocks (Ávila et al. 2001; Súarez Pascua 2002; Dzib-Castillo 2003; De Beenhouwer et al. 2016); however, no study we know of has evaluated the relationship between coffee system management intensity, site conditions (e.g. mean annual precipitation), and C stocks of coffee trees within these systems. Of the studies reporting on coffee management and C stocks, only a small subset (seven studies) reported carbon stocks for coffee trees alone. Many studies only give C stocks of shade trees (Suárez 2002; Goodall et al. 2015) and others report a single AGC value without discerning between the individual components (i.e. shade trees, coffee trees, etc.) that make it up (Richards and Mendez 2014; De Beenhouwer 2016). We included data on total
AGC (Table 2) yet, because previous studies have reviewed AGC, the focused of this paper will be on individual coffee plants.

We analyzed seven studies in five countries across the coffee belt to determine how management and site conditions affect C stocks in coffee trees (Figure 1). More than half of the studies used were based in Latin America. Traditional rustic and traditional polyculture systems were not included in this analysis as few studies of these systems were encountered in the literature. For each study, we identified the mean annual precipitation and temperature as well as the C stocks reported for the coffee trees. Linear regression tests were run in SPSS (version 21) to analyze the relationship between site conditions (temperature and precipitation) and coffee C stocks for sun and shade systems.

Aboveground carbon stocks for coffee trees ranged from $0.2 \pm 0.03 \text{ Mg \, ha}^{-1}$ in an unshaded monoculture in Peru (Ehrenbergerová et al. 2015) to $12.90 \pm 0.88 \text{ Mg \, ha}^{-1}$ in a commercial polyculture in Guatemala (Schmitt-Harsh et al. 2012). Three studies included carbon stocks for coffee trees in both shaded and unshaded systems at the same site; however, there was no clear relationship between level of shade management and coffee C stocks (Table 2).

*Table 2. Location, site conditions, management intensity and C stocks of coffee systems.*

<table>
<thead>
<tr>
<th>Location</th>
<th>Holdridge Life Zone</th>
<th>Classification (Moguel &amp; Toledo 1999)</th>
<th>Aboveground C Stocks (Mg ha$^{-1}$)</th>
<th>Coffee C stocks (Mg ha$^{-1}$)</th>
<th>Method of calculating coffee C stocks</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Guatemala</td>
<td>montane moist forest</td>
<td>commercial polyculture</td>
<td>73.18 ± 5.30</td>
<td>12.90 ± 0.88</td>
<td>Species-specific allometry</td>
<td>Schmitt-Harsh et al. 2012</td>
</tr>
<tr>
<td>Country</td>
<td>Forest Type</td>
<td>Climate</td>
<td>Elevation</td>
<td>Management</td>
<td>Species</td>
<td>Specific Allometry</td>
</tr>
<tr>
<td>-----------</td>
<td>-------------------------------</td>
<td>---------</td>
<td>-----------</td>
<td>----------------</td>
<td>------------------</td>
<td>---------------------</td>
</tr>
<tr>
<td>Indonesia</td>
<td>premontane wet forest</td>
<td>2500 mm</td>
<td>21.2 °C</td>
<td>commercial polyculture</td>
<td>69</td>
<td>18.4 ± 4.0</td>
</tr>
<tr>
<td></td>
<td>780-1700 m asl</td>
<td></td>
<td></td>
<td>unshaded monoculture</td>
<td>11.44</td>
<td></td>
</tr>
<tr>
<td>Costa Rica</td>
<td>tropical moist forest</td>
<td>2300 mm</td>
<td>21 °C</td>
<td>shaded monoculture</td>
<td>23.0 ± 0.7 (I. densiflora)</td>
<td>9.1 ± 0.6</td>
</tr>
<tr>
<td></td>
<td>1180 m asl</td>
<td></td>
<td></td>
<td>unshaded monoculture</td>
<td></td>
<td>8.5 ± 0.4</td>
</tr>
<tr>
<td>Costa Rica</td>
<td>tropical moist forest</td>
<td>2115 mm</td>
<td>22 °C</td>
<td>shaded monoculture</td>
<td>12.3 ± 5.9 (E. deglupta)</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1000-1100 m asl</td>
<td></td>
<td></td>
<td>unshaded monoculture</td>
<td>10.6 ± 4.0 (E. poeppigiana)</td>
<td>10.4 ± 3.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>commercial polyculture</td>
<td>10.4 ± 3.5</td>
<td>10.4 ± 3.5</td>
</tr>
<tr>
<td>Costa Rica</td>
<td>premontane wet forest</td>
<td>2000-2500 mm</td>
<td>23 °C</td>
<td>shaded monoculture</td>
<td>19.3 ± 12.1 (conventional)</td>
<td>3.4 ± 2.2 (conventional)</td>
</tr>
<tr>
<td></td>
<td>200-1250 m asl</td>
<td></td>
<td></td>
<td>unshaded monoculture</td>
<td>30.2 ± 9.7 (organic)</td>
<td>2.3 ± 1.7 (organic)</td>
</tr>
<tr>
<td>Peru</td>
<td>tropical moist forest</td>
<td>1590 mm</td>
<td>17.8 °C</td>
<td>shaded monoculture</td>
<td>30.3 ± 3.2 (Inga spp.)</td>
<td>1.6 ± 0.3 (Inga spp.)</td>
</tr>
<tr>
<td></td>
<td>1540-1660 m asl</td>
<td></td>
<td></td>
<td>unshaded monoculture</td>
<td>62 ± 4.7 (Pinus spp.)</td>
<td>2.8 ± 0.6 (Pinus spp.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>53.5 ± 3.1 (Eucalyptus spp.)</td>
<td>1.5 ± 0.4 (Eucalyptus spp.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1 ± 0.1</td>
<td>0.2 ± 0.03</td>
</tr>
<tr>
<td>Togo</td>
<td>premontane moist/dry forest</td>
<td>1400 mm</td>
<td>21–28°C</td>
<td>shaded monoculture</td>
<td>67</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>300-500 m asl</td>
<td></td>
<td></td>
<td>unshaded monoculture</td>
<td>13.8</td>
<td>9</td>
</tr>
</tbody>
</table>
Coffee C stocks under shade management were less affected by temperature than coffee in unshaded monocultures (Figure 5a). For shade coffee, the difference in C stocks between sites at the high and low ends of the temperature gradient was 5.5 Mg ha\(^{-1}\) (Table 2). Additionally, the line of best fit for shade coffee had an R\(^2\) of 0.053, which indicates that, under shade management, local temperatures are not an important determinant of coffee C stocks (Figure 5a). Sun coffee displayed a greater difference of 8.8 Mg ha\(^{-1}\) between C stocks the high and low end of the temperature gradient (Table 2). In addition, the R\(^2\) of 0.754 indicates that C stocks are more likely to be predicted by temperature, showing that as temperature increases, so do coffee C stocks (Figure 5a). These data suggest that shade trees, which buffer against large temperature fluctuations, may help stabilize coffee tree growth at its upper and lower temperature extremes (DaMatta 2004).

![Map showing mean annual temperatures of coffee study sites.](image)

*Figure 4. Locations and reported mean annual temperatures of coffee study sites.*

As predicted, coffee trees with the largest mean C stocks were found in sites at the upper end of the precipitation gradient, likely because greater amounts of rainfall increase overall site
productivity (Figure 5b). At lower precipitation levels, it becomes unclear whether coffee in sun or shade systems stores the most C. One study, which received 1400 mm precipitation per year, found that sun coffee stored slightly more C than shade coffee (Dossa et al. 2008). However, the opposite result was seen at 1600 mm precipitation (Ehrenbergerová et al. 2015). Whether there was a significant difference between C stocks in sun and shade systems was not reported. Nonetheless, C stocks for coffee under shade management appear to be more affected by precipitation that coffee in unshaded monocultures (Figure 5b).

Figure 5. Effect of temperature (a) and precipitation (b) on coffee carbon stocks under sun ($R^2 = 0.1718$) and shade ($R^2 = 0.4063$). Points represent mean C stocks for sun (yellow) and shade (green) for individual studies.
3 Pests & Diseases

Agricultural pests and diseases can cause extensive crop losses and, in some cases, complete crop failure, making them a serious concern for farmers around the globe. Coffee in particular has been greatly affected by pests and diseases (see section 1.4), especially when the accidental introduction of alien species occurs (Staver et al. 2001). Between 1988 and 1990, global coffee production faced $2.8 billion in losses due to insect pests and another $2.8 billion in losses from disease-causing pathogens (Oerke et al. 1995). In addition, costs associated with chemically controlling pests and diseases has been rapidly rising in recent decades, reducing the profit margin for many small-scale coffee growers (Waller et al. 2007). Coffee berry borer (H. hampei) and coffee leaf rust (H. vastatrix) have been identified as the most devastating coffee pest and disease respectively (Jaramillo et al. 2009; Waller et al. 2007); therefore, it is critical to understand how coffee system management affects their prevalence.

3.1 Coffee berry borer

The coffee berry borer is a beetle (Scolytidae) native to Central Africa that is now distributed throughout the tropics in all coffee-growing regions (Vega et al. 2009). It feeds on coffee fruits and seeds and poses the greatest economic threat to coffee production (Baker 1984; Damon 2000). The coffee berry borer has a restricted range, which historically prevented it from inhabiting high altitudes; however, range shifts seen in recent decades have been attributed to climate change (Waller et al. 2007). Coffee berry borers can be managed through a number of methods, from pesticide application to natural control by local predators, such as parasitoids, ants, and birds (Vega et al. 2009).
There is disagreement over whether shaded or sun plantations are better for naturally controlling pest populations. Traditional coffee systems are thought to be more resistant to pest outbreaks than modern coffee systems due to higher levels of diversity and structural complexity (Staver et al. 2001; Soto-Pinto et al. 2002); however, consistent experimental evidence to support this claim is lacking. Soto-Pinto et al. (2002) found that the presence or absence of shade did not affect coffee berry borer abundance; however, their work in rustic coffee systems also showed a lower overall incidence of coffee berry borer compared to other studies. In contrast, Wringley (1988) determined that shaded systems had a greater abundance of coffee berry borer, while Armbrecht and Gallego (2007) found that coffee berry borers in shaded systems in Colombia were more likely to be preyed upon by ants. These disparities in conclusions indicate that more complex site- and coffee system specific factors are likely at play.

Climatic conditions such as rainfall intensity and frequency as well as temperature can greatly affect insect pests (Bale et al. 2002). It has been suggested that, of these factors, temperature is the most influential on pest dynamics, with warming temperatures leading to decreased insect mortality and less time between generations (Bale et al. 2002). This has been shown experimentally where, under lab conditions, coffee berry borer developed more rapidly at all stages with increasing temperature (Jaramillo 2009). Therefore, regions that experience climate change-induced temperature increases may see increased severity and frequency in coffee berry borer outbreaks. For instance, the coffee berry borer was absent from SW Ethiopia prior to 1984 due to low temperatures inhibiting development; however, the coffee berry borer is now widespread throughout the region. In countries like Colombia, where plants flower multiple times throughout the year, increased turnover of coffee berry borer generations due to increased temperature could significantly reduce production (Jaramillo 2009). Predictions of Jaramillo et
al. (2009) were also confirmed by farmer interviews in Uganda, which reported the appearance and rapid proliferation of coffee berry borer in the region in recent years (Jassongne et al. 2013).

In addition, changing weather patterns may reduce positive interactions between coffee and beneficial insects (Rosenzweig et al. 2001). For instance, soil-dwelling ants in Brazil have been identified as important predators of coffee berry borer (Armbrecht and Gallego 2007); however, water logged soils, brought on by abnormally cool, wet conditions may reduce ant populations on coffee plantations (Rosenzweig et al. 2001).

3.2 Coffee leaf rust

Coffee leaf rust (*Hemileia vastatrix*) is a fungal disease that coevolved with coffee in West Africa (Waller et al. 2007). Once infected, coffee trees fail to effectively photosynthesize and leaves die prematurely (Brown et al. 1995). Like the berry borer, leaf rust is found in almost all coffee producing regions (Waller et al. 2007).

As previously discussed, coffee modernization was pursued in part because it was that reduced shade would help suppress disease outbreaks. Recent research on the relationship between shade and coffee leaf rust has suggested that the modernization of coffee plantations in the late 20th century may have been somewhat misguided. A study comparing shaded and unshaded coffee systems in Mexico found that the presence of shade did not significantly affect the prevalence of coffee leaf rust (Soto-Pinto et al. 2002). This contradicts previous research that found shade systems experienced more severe outbreaks of leaf rust, likely due to more humid microclimates (Monterroso 1999). Again, these conflicting findings indicate that more complex factors than the simple sun versus shade dichotomy are at play. Avelino et al. (2006) found that landscape characteristics, such as the land use adjacent to coffee systems, could be a major
predictor of leaf rust outbreaks. For instance, coffee systems adjacent to cattle pastures are more exposed to wind, which may make these systems more vulnerable to the disease.

As with pests, climate change may lead to changes in coffee disease dynamics. Air currents can act as a vector for disease, carrying pathogens long distances and making it incredibly difficult to prevent the spread of diseases regionally (Rosenzweig et al. 2001). Therefore, future shifts in air currents could increase leaf rust prevalence. In addition, warmer temperatures can exacerbate coffee leaf rust, so areas most affected by climate change may also experience greater pressure from this disease (Waller et al. 2007).

3 Conclusions

In total, we reviewed 14 studies that estimated C stocks in coffee systems throughout the coffee belt. Of these, only seven reported on total carbon of coffee trees specifically (Table 2). The remaining studies reported AGC as a lump sum, so coffee C stocks could not be determined from the results (Ávila et al. 2001; Suárez Pascua 2002; Dzib Castillo 2003; Castellanos et al. 2010; Soto-Pinto et al. 2010; Richards and Mendez 2013; De Beenhouwer 2016). Richards and Mendez (2013) measured only C stocks in shade trees, excluding lianas, herbaceous species, and coffee trees in their study site. This not only fails to get a complete picture of AGC for their site, but also makes it difficult to draw comparisons between C stocks across sites. Van Rikxoort et al. (2014) conducted a thorough study of C stocks under four management schemes throughout Latin America; however, individual site conditions were unreported so we could not differentiate between optimal and suboptimal sites.

From the seven studies where individual C stocks were reported, we determined that levels of shade management did not directly drive coffee C stocks. Instead, site-specific conditions, particularly precipitation and temperature, appear to interact with shade management
and influence coffee C stocks. Temperature was more important for sun coffee than shade coffee in determining C stocks with higher temperatures associated with more C storage (Figure 5a). Similarly, mean precipitation was more important for shade coffee so that areas with greater amounts of precipitation stored more C (Figure 5b). However, an increased sample size, with sites represented across the coffee gradient would help better elucidate the relationship between coffee C, management, and site conditions.

The relationship between coffee shade management, pests, and diseases is also unclear. Existing research has provided mixed results on how the incorporation of shade in coffee systems affects the prevalence of coffee berry borer and coffee leaf rust (Soto-Pinto et al. 2002; Armbrecht and Gallego 2007) and there is additional uncertainty in how these relationships will change under future climate change. Further research is needed to evaluate how site-specific conditions affect coffee system resistance to pests and diseases so coffee producers can be adequately prepared for the future.

While shade coffee is not a substitute for native forest, under proper site conditions, coffee system C stocks can be optimized. Future studies of coffee and carbon should take into account and report on the site-specific impacts of management, which are critical for effective land-use planning. Only with this understanding can the full potential of agroforestry systems in climate change mitigation be realized.
References


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