Shade coffee: update on a disappearing refuge for biodiversity

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In the past three decades, coffee cultivation has gained widespread attention for its critical role in supporting local and global biodiversity. In this synthetic overview, we present newly gathered data that summarize how global patterns in coffee distribution and shade vegetation have changed and discuss implications for biodiversity, ecosystem services, and livelihoods. While overall coffee area has decreased by 8% since 1990, coffee production and agricultural intensification has increased in many places and shifted globally, with production expanding in Asia while contracting in Africa. Ecosystem services such as pollination, pest-control, climate regulation, and nutrient sequestration are generally higher in shaded coffee farms, yet many coffee growing regions are removing shade trees from their management. While it is clear that there are ecological and socio-economic benefits associated with shaded coffee, we expose the many challenges and future research priorities needed to link sustainable coffee management with sustainable livelihoods.

Keywords: *agriculture, agroforestry, corridor, ecosystem services, tropical ecology*

Across the world, more than 400 billion cups of coffee are consumed per year (Illy 2002). Coffee is among the most valuable legally traded commodities from the developing world (FAO 2010), engaging between 14 and 25 million families in production, and millions more in the processing, roasting, and selling of coffee (Donald 2004). In the last two decades, the value of shade-grown (hereafter ‘shade’) coffee farms for biodiversity conservation and ecosystem service provision has gained widespread attention from the public and scientific communities (De Beenhouwera et al. 2013, Jha et al. 2012, Perfecto et al. 1996, Tscharntke et al. 2011). In this short time span, global coffee distribution patterns and local coffee management practices have exhibited dramatic changes, with major implications for ecology and livelihoods. In this paper, we investigate trends in global coffee distributions and cultivation practices, and we review the potential impacts of these geographic and management changes on biodiversity, ecosystem services, resilience to climate change, and sustainable livelihoods.

1. Shifting global production patterns and management practices

a. Past and current distribution of coffee

The two coffee species of commercial value, *Coffea arabica* and *Coffea canephora* ("robusta"), both originate from Africa, with the former having generally preferred taste qualities and the latter exhibiting higher yield and pest-resistance (ITC 2011, ICO 2013). *C. arabica* dominates global coffee landscapes, accounting for 60% of all volume (ITC 2011). While coffee's center of origin lies in Ethiopia, major global dispersal of the bean occurred when Arab and European traders introduced the beverage to Western Europe in the early 1500s (Ukers 1922). By the latter half of the 1800s, coffee plantations of both *C. arabica* and *C. canephora* flourished throughout the American tropics, and by the 1970s its cultivation dominated more than 8.8 million ha of tropical landscapes. Between 1970 and 1990, global coffee area and average yields increased by 25% (8.8 to 11.1 million ha, and 433 to 543 kg/ha, respectively), and global production increased by 58% (FAO 2010). Interestingly, although global area decreased to 10.2 million ha between 1990 and 2010 (the year with most recent comprehensive data), production still climbed 36%, which provides evidence of overall intensification in several key countries (e.g. Brazil and Colombia), coffee abandonment in others (e.g. Burundi and Kenya), as well as rapid expansion of high-yielding coffee in new countries (e.g. Vietnam and Indonesia)(FAO 2010). Brazil, for instance, saw a 112% jump in production with only a 12% increase in coffee area between 1996 and 2010, growth spurred by intensification that resultued in an 89% yield increase over that period (FAO 2010), and recognition from coffee experts that production there has been highly industrialized (Croce 2013, Izada 2013). Since the mid-1980's, exports of "robusta" coffee have increased by 92%, led by a number of Asian countries, with Vietnam being the prime example, exhibiting hand-in-hand increases in both area and intensification (Guingato et al. 2008, ITC 2011). Robusta yields there soared from a historical average of 450 kg/ha prior to the 1950's to 1558 kg/ha by 2004 (D'haeze et al. 2005), more than double the global yield average at the time, revealing that a species shift alone does not explain yield increases. Given that coffee area decreased globally by 9% between 1990 and 2010, whereas world production increased by 36%, we posit that intensification is one of the major drivers of shifting coffee cultivation patterns.

A closer look reveals that the shift in production between 1990 and 2010 was regional, as 45% of all nations exhibiting decreases hailed from Africa, while Asian countries accounted for 35% of those with increased production (Fig. 1). When the first comprehensive studies of coffee and biodiversity emerged in 1996, the top three producing countries were Brazil, Colombia, and Indonesia. Currently, Brazil, Vietnam, and Indonesia top the list, accounting for 57% of the 8.2 million metric tons in 2010. In Vietnam alone, cultivated area increased by 731%, yields by 45%, and total production by 1102%, between 1990 and 2010 (Fig. 1). In contrast, the past 20 years reveal coffee area declines exceeding 20% in Ecuador, Colombia, Côte d'Ivoire, Mozambique, Madagascar, Tanzania, and Rwanda (FAO 2010).

The contrasting and heterogeneous changes in global coffee cultivation result from multiple factors, including region-specific economic development patterns, political conflict, cultural practices, land values, wages, and labor. For example, deforestation accompanied increases in coffee area in Vietnam, Indonesia, Nepal, and Panama (D'haeze et al. 2005, O'Brien and Kinnaird 2003, FAO 2010). In contrast, in places where coffee area has declined, such as Costa Rica and Ecuador, the expansion of high-yield agriculture has caused a decrease in coffee prices, resulting in the abandonment of marginal agricultural lands (Aide and Grau 2004, FAO 2010), in combination with increased land prices due to urbanizaion. The result is an increase in global production despite decreases in overall coffee area (Fig. 1). Higher land values due to ex-urbanization often displace coffee cultivation in places like Panama's Boquete and Chiriquí regions, Costa Rica, and Guatemala, areas now popular as retirement destinations (Zeltzer 2008). In a number of countries, waves of political and social instability have reduced investment in coffee cultivation (e.g., Rwanda, Nicaragua pre-1995, Colombia), only to have sustained global prices post-2005 spur expansion in other countries (Rueda and Lambin 2013). In other regions, the draw of better urban wages (e.g., Costa Rica) or displacement by other cash crops like cacao (e.g., Côte d'Ivoire) has reduced the area of coffee production.

Despite variation in global coffee production, the majority of coffee is still produced by smallholders managing fewer than 10 ha of coffee (reviewed in Jha et al. 2012), as documented in Asia and Africa (e.g., Jena et al. 2012, Neilson 2008, respectively). Likewise, in Central America, smallholders represent 85% of coffee producers but control only 18% of coffee production lands (CEPAL 2002). In some coffee producing countries, such as Rwanda, coffee farm sizes are so small that the majority of farms are measured by number of coffee trees instead of hectares (e.g., 300 bushes) compared to many Mesoamerican smallholder farms, where stand densities as high as 6700 coffee bushes per ha can be found (Méndez et al. 2007). These patterns in farm size tend to shift depending on coffee prices and government incentives, as evidenced in

Latin America, where a decrease in the number of large estates and an increase in the number of smallholder and micro-producers occurred directly after the 1999 coffee crisis, when coffee prices dropped to century lows (Topik et al. 2010). In the Costa Rican coffee district of Agua Buena, the proportion of farmland dedicated to coffee production diminished from 52% to 24% between the years 2000 and 2009, while the proportion of pasture land increased from 31% to 50%, largely due to basement-level international coffee prices (Babbin 2010). This example highlights the need for locally and regionally specific research into the social-ecological causes and consequences of changing coffee production patterns.

2. Vegetation management

In addition to global and regional shifts in coffee cultivation, within-farm vegetation management has changed dramatically across centuries of coffee production. Farm-level coffee management involves distinctions in elevation, sun exposure, soil conditions, density of bushes, presence of additional wild or cultivated plants, age of bushes and pruning style, and agrochemical use, among other factors (Moguel and Toledo 1999, Tscharntke et al. 2011). The most traditional coffee growing practices, as seen in 'rustic' coffee, involves growing coffee under a diverse canopy of native forest trees in high to moderate shade. As vegetation management is 'intensified', plantations have fewer shade trees, fewer shade tree species, lower canopy cover, and fewer epiphytes (Moguel and Toledo 1999). Shade management intensification is often also accompanied by increased use of synthetic agrochemicals (e.g. pesticides, fungicides, herbicides, and fertilizers). Finally, at the most 'intensified' end of the vegetation management spectrum, coffee is grown in full sun.

Interestingly, examining coffee vegetation management across a number of countries reveals that shade cover management is heterogeneous, and the changes in its global coverage are region-specific. In Latin America, between 1970 and 1990, nearly 50% of all shade coffee farms were converted to low shade systems (Perfecto et al. 1996). Changes varied by country, ranging from 15% of farms in Mexico to 60% in Colombia (Perfecto et al. 1996). Since the 1990s, regions with intensively managed coffee, such as Brazil and Colombia, still remain largely devoid of diverse shade systems, and have either maintained or increased areas of sun-coffee (Guhl 2004, Croce 2013). From the 1990s to 2010, most Latin American countries decreased the percent of total coffee production area dedicated to traditional diversified shade coffee production, but at a slower rate than from 1970 to the 1990s. Based on the ten countries for which we have data from both the 1990s and the 2010s, we find that half of these countries experienced a decrease in the percent of all coffee under traditional shade management (Colombia, Costa Rica, El Salvador, Guatemala, and Nicaragua). However, because coffee production areas expanded in the many of the remaining countries and several of these countries reported higher percentages of shade production (e.g. Honduras, Panama), our calculations suggest that there was an overall 11% increase in the area of land dedicated to diverse shade coffee production.

However, examining at a more global scale, if we include all 19 countries for which we have 2010 data, approximately 41% of coffee area is currently managed with no shade, 35% with sparse shade, and only 24% with traditional diverse shade (supplemental table S1, figure 2). This indicates that global shade coffee cultivation is lower than our estimates for 1996 (about 20% lower), when approximately 43% of all coffee areas surveyed were cultivated in traditional diverse shade. For example, between 2000 and 2009, coffee-growing regions in Costa Rica experienced a 50% loss of shaded coffee (and shade trees) in the process of conversion to sun-coffee, pasture, or other crops (Bosselmann 2012). The sun-coffee management style has also dominated many new coffee growing regions, exemplified in Vietnam's dramatic expansion of coffee, and also evident in Thailand and Indonesia (Fig 2). In contrast, only a few countries, (Colombia, Haiti, India), have continued managing diverse shade since the 1990s in all or parts of their coffee regions (Fig 2).

Coffee vegetation management patterns are nuanced and often depend on farm size, available alternatives, national and regional politics, risk aversion strategies and development funding. For example, 81% of the coffee in Nicaragua and El Salvador grew under a shade canopy in 1996, and while recent surveys document declines in shade tree diversity since then, these declines mostly occurred on larger farms, with many smallholder cooperatives preserving high levels of biodiversity, including more than 100 species of shade trees found on less than 30 farms (Méndez et al. 2010a). Similarly, in the Kodagu coffee-growing region of India, nearly 100 tree species can still be found in smallholder coffee farms (Bhagwat et al. 2005).

While it is clear that coffee management styles remain unevenly distributed both within and among countries, the causes for this high level of variation have never been systematically reviewed. We document several broad trends and posit that coffee vegetation management style is influenced primarily by five main factors: 1) cultivar origin, 2) perceived resistance to disease, primarily the coffee leaf rust, 3) perceived increases in yield, 4) socio-economic decisions related to group membership and livelihoods, and 5) shifting economic incentives linked to global coffee markets and value chains. Here, we present a comprehensive review on these five major factors and document the evidence supporting and contradicting each.

a. Cultivar origin

The two dominant coffee species cultivated globally are *Coffea arabica* (Arabica) and *C. canephora* (Robusta), which have distinct origins and cultivation histories and thus differ in flavor, ideal growing conditions, resistance to pests/pathogens, and yield, among other traits. Most notably, while Arabica and its cultivars grow best at mid-high elevation (600-2000 meters), exhibiting maximum photosynthetic rate at moderate temperatures and higher shade levels, Robusta and its cultivars are tolerant of lower-elevation (0-800 m) and full sun exposure, growing best at temperatures between 24 and 30° C (Wilson 1999). The distinctions between these species, their tolerance for temperature shifts, the development of disease resistant cultivars, along with a number of socioeconomic factors described in this review, underlie much of the variations in current coffee vegetation management practices seen across the globe.

b. Coffee diseases and yield

Fungi cause most major coffee diseases (e.g., coffee leaf rust, brown eyespot, and coffee berry disease), primarily affecting *Coffea arabica* (Staver et al. 2001), while *C. canephora* varieties remain more resistant (FAO 2012). Coffee leaf rust (*Hemileia vastatrix*) is the main disease of *C. arabica* in Latin America (Avelino et al. 2007), with the latest (2012-2013) outbreak lowering harvests by 10-70% in several Latin American countries, including Peru (JNC 2013), Mexico (GAIN Report, 2013), Colombia, Costa Rica, Nicaragua, Honduras, Panama, El Salvador, and Guatemala (Virginio 2013). Efforts to control coffee leaf rust in the 1970s and 1980s led to much of the 'modernization' of coffee cultivation practices in Guatemala, Honduras, Panama and other countries, and include practices such as the use of supposedly disease-resistant high-yielding varieties, the reduction of shade, and the increased planting density of coffee bushes (Rice and McLean 1999).

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. Vegetation complexity may increase coffee leaf spot (*Mycena citricolor*)(Avelino et al. 2007), 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, as rust incidence increases with humidity independent of shade levels (Staver et al. 2001). Other studies document no correlation between shade and leaf rust on *Arabica* varieties (e.g., Soto-Pinto et al. 2002, Lopez Bravo et al. 2012). In fact, moderate shade (35-65%) can actually reduce brown eyespot (Staver et al. 2001), weeds, and the citrus mealy bug, and can increase the effectiveness of parasites of other pests (Perfecto et al. 1996, Staver et al. 2001). Additionally, moderate shade levels can hinder fungal diseases by creating windbreaks and slowing the horizontal spread of coffee leaf rust spores (e.g., Soto-Pinto et al. 2002). Thus, coffee disease cannot be reduced by shade management alone, but in combination with modified humidity, predator management, and local and regional landscape management.

c. Shade, yield, and quality

The interactions between shade, yield, and ‘cup’ quality are very important to farmers, the coffee industry, and consumers. Yield-focused government incentives such as Coffee Research Institutes, created in the 1970s and 1980s (e.g., PROCAFE in El Salvador, ANACAFE in Guatemala, ICAFE in Costa Rica, and IHCAFE in Honduras) promoted the reduction or removal of shade cover (Staver et al. 2001), created extension programs to support technified practices, and financed programs that often included free or subsidized agrochemicals (Rice and McLean 1999). While many farmers cite increases in coffee yields as the main reason for removing shade trees and native vegetation, the ecological evidence supporting decreased shade and increased coffee yield is far from clear. Studies that have categorically compared yield in low vs. high shade treatments have found lower yields with shade, higher yields with shade, and no difference; however, studies that examine a continuous gradient of shade predominantly reveal that intermediate shade levels (~35-50%) produce the highest coffee yield, likely due to the balance maintained between optimal temperatures in shaded environments and optimal photosynthetic rates in unshaded environments (Soto Pinto et al. 2000 and references therein). While it is difficult to compare findings across studies due to geographical differences, it is clear that yield is not solely or linearly linked to shade tree density or diversity.

Recent work also shows that cup quality is the result of a variety of interacting factors that include environmental conditions, field management, adequate processing and drying, as well as roasting. Surprisingly, breeding efforts for coffee have largely ignored quality and focused mostly on increasing yields and disease resistance (Montagnon et al. 2012). Research related to shade effects on 'Catimor' varieties points to shade's positive effect on coffee bean and cup quality in lower elevations (≤ 500 m) and positive to negative effects on cup quality at higher elevations (Bosselmann et al. 2009). 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 (Muschler 2001). 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.

d. livelihood, cooperatives, and shade coffee management

Farm size, cultural history, and relationship with cooperatives can influence farmer management decisions and shade vegetation (Moguel and Toledo 1999). In Veracruz, Mexico, small-scale producers (1-5 ha) used lower levels of agrochemicals per farm than larger scale farmers (>45 ha), resulting in fewer soil and water contamination problems. However, many of these small-scale farmers are slowly adopting several of the intensified management practices utilized by larger growers (Guadarrama-Zugasti 2008). In El Salvador and Nicaragua, small (1-10 ha), individually-managed farms contained higher levels of shade tree diversity compared to larger (>100 ha) collectively managed holdings (Méndez et al. 2007); furthermore, tree diversification levels were highest for cooperatives that clearly defined who was going to benefit from shade tree products (Méndez et al. 2009). In both of these countries, individually managed farms adopted vegetation diversification in order to generate a higher variety of tree products and on-farm benefits (Méndez et al. 2010a). These farmers managed their coffee plantations both for household consumption products, as well as income from coffee. In contrast, collectively managed farms focus almost entirely on producing coffee for income, due in part to the challenge of distributing both the work and the benefits to obtain more on-farm products. The only non-coffee product on which collective farm members are dependent and actively collect is firewood; collective cooperatives have an open policy for its members to access firewood for household use (Méndez et al. 2007, Méndez et al. 2009). Thus, well organized cooperatives, if present, can be essential for coordinating collective action that can help smallholders manage the distribution of benefits and retain land titles (Raynolds et al. 2007), potentially creating key institutional environments for sustainable land stewardship.

In addition to land titles, a number of assets are important for optimal livelihood: participation in a cooperative or other local association, and access to land, water, loans, houses, and equipment (e.g., Bacon et al. 2008). Research shows that individuals working at the producing end of the coffee value chain (i.e. the farmers and countries) continue to receive a very small fraction of the profits and coffee pickers and laborers (often migratory) are the most marginalized actors within the coffee value chain (Oxfam 2002), since they are vulnerable to shifts in production, climate, and market demands (Bacon et al. 2008, CEPAL 2002) and are paid by the pound or volume of coffee cherries harvested, making as little as $2 to $10 per day in many parts of the world (Oxfam 2002). For example, between 2000 and 2001, Ugandan farmers received $0.14 for a kilo of unprocessed coffee that at retail would fetch more than $26.00 as instant coffee in the United Kingdom (Oxfam 2002). Accounting for weight loss during the processing and roasting of the coffee, this represents a 7000% price increase in the journey from farm to shopping cart (Oxfam 2002). Other cases are less lopsided; Colombian farmers received 23-25% of the value added for coffee sold into specialty and mainstream markets in 2010 (Rueda and Lambin 2013). However, while specialty coffees often result in higher prices at the farm gate, questions remain about the extent to which the benefits of higher retail prices translate into higher revenues for farmers and communities (Rueda and Lambin 2013). Broad-based job losses in coffee farming have decreased since 2005, but seasonal hunger, marginalization, and vulnerabilities persist (Bacon et al. 2008, Méndez et al. 2010b).

e. Shifting economic incentives linked to global coffee markets and value chains

One avenue to address declines in coffee profits and sustainable management is through the specialty coffee market, which currently claims 37% of coffee volume but nearly 50% of the coffee value in the 2012 US coffee market, worth an estimated $30-32 billion dollars (SCAA 2012). This market has expanded rapidly in the past 20 years with estimates of total retail specialty coffee sales, excluding Wal-Mart, continuing to increase in the past decade (Fig. 3). The specialty coffee market supports a distinct value chain. By definition, specialty coffees distinguish themselves from bulk coffee based on a variety of factors that include ‘quality’ (Läderach et al. 2006), ‘sustainability’ and/or closer relationships with growers (Bacon et al. 2008). Within the specialty coffee market, “Sustainably certified” coffees encompass several types of certifications, with Fair Trade focusing on the trade relationships, and Organic requiring soil conservation and prohibiting agrochemicals and genetically modified crops, among other criteria (Méndez et al. 2010b). Smithsonian’s Bird Friendly certification program has the highest agro-environmental standards, requiring organic certification and more than ten species of shade trees, as well as guidelines to conserve soil and water. Rainforest Alliance, Utz Certified, and Fair Trade also have several agro-environmental standards restricting the use of many of the most toxic pesticides and herbicides, although synthetic fertilizers and some pesticides, fungicides, and herbicides are permitted.

A trend that has continued since the 1990s is the significant rise in the quantity of coffee with one or more ecolabel. It is estimated that more than 10% of all coffees sold in 2007 carried at least one sustainability certification and it is expected that this percentage will continue to increase rapidly (Giovanucci et al. 2008). In addition to the certifications previously mentioned, firms, non-profit organizations, and even governments continue to partner to generate an expanding number of different labels and sustainable coffee initiatives. Several key examples include the Common Code for the Coffee Community (4C), and two initiatives started by large coffee companies that do roasting and retailing, Starbuck’s Coffee And Farmer Equity (CAFÉ) practices and Nestle's Nespresso AAAA Sustainable Quality Program. These latter two programs function by setting social and environmental criteria for certification and have grown rapidly in the past decade, with more than 160 million pounds of coffee certified in 2006 alone (Giovanucci et al. 2008).

A closer look at coffee profits and farmer livelihoods reveals that Fair Trade and Organic certifications are able to provide a number of benefits to smallholder farmers, although livelihood challenges persist (Arnould et al. 2009, Méndez et al. 2010b). For example, farmers that participate in cooperatives connected to Fair Trade often have more access to credit and technical support (Méndez et al. 2010b), and often receive higher prices for their coffee, buffering exposure to falling coffee commodity prices and diminishing the negative consequences of unexpected challenges, such as food shortages, hurricanes, and earthquakes (e.g, Raynolds et al. 2007). However, Fair Trade does not necessarily improve access to food through purchasing or production (Arnould et al. 2009, Méndez et al. 2010b). Furthermore, although certifications are often associated with higher coffee prices, the small volumes sold and additional certification costs often counterbalance added income at the household level, especially as the real price premiums delivered to farmers have declined during the past decades (Bacon 2010). This suggests that major changes are required to provide a strong incentive for sustainable coffee management via the certification processes.

3. Biodiversity, ecosystem services, connectivity, and resilience to climate change

a. Biodiversity and ecosystem services

Shaded coffee plantations are increasingly valued for their contributions to biodiversity conservation and the provisioning of ecosystem services (Beenhouwer et al. 2013, Tscharntke et al. 2011). Since the 1990s, shade coffee has been noted for its contributions to conserving plant, arthropod, bird, bat, and non-volant mammal diversity (Perfecto et al. 1996, Donald 2004). More recent studies have documented patterns of bird, ant, and tree biodiversity decline specifically in response to decreasing vegetation cover and increasing management intensity (Philpott et al. 2008a). Biodiversity declines within coffee systems are of particular concern given that ecosystem services (ES) such as pollination, pest control, erosion control, watershed management, and carbon sequestration, are worth billions annually and are largely a function of biodiversity levels (Wardle et al. 2011). Thus, as a whole, ecosystem services tend to decline as forests are converted to shade coffee, and shade coffee is converted to low shade coffee systems (Beenhouwer et al. 2013). Based on our review, more than seventy studies have directly measured unique ecosystems services across varying vegetation management styles, including pollination (7 studies), pest-control (42 studies), climate regulation (13 studies), and nutrient cycling (10 studies). While distinct methodologies and methods of measuring response variables (e.g. predator species richness vs. predator abundance) complicate meta-analyses for each unique ecosystem service, we found positive effects of shade on ecosystem services in approximately 58% of pollination studies, 60% of the pest control studies, 100% of the climate regulation studies, and 93% of the nutrient cycling studies (Table 1, Literature Search details in Table S2).

Specifically, vegetation complexity at the canopy level can lead to lower weed densities (Beer et al. 1998) and because many shade trees fix nitrogen (e.g. *Inga* spp.), shade trees can increase the nutrient content of soils (Beer et al. 1998). Scant shade coffee systems (1-3 tree species) sequester an additional 53-55 tons of carbon per hectare in above ground biomass compared to unshaded coffee monocultures (Palm et al. 2005). In Mexico, Soto-Pinto et al.

(2010) found that *Inga*-shaded organic coffee maintained aboveground carbon (56.9 tons C per hectare) and in the soil (166 tons C per hectare) to an equal extent as nearby forests, and traditional polyculture coffee maintained more carbon than all other land-use types examined (Soto-Pinto et al. 2010). If we consider that scant shade systems sequester an additional 53 tons of carbon per hectare (Palm et al. 2005), then the conversion of even 10% of all sun coffee systems (currently covering 3.1 million ha) to even scant shade cover, would result in 1.6 billion additional tons of aboveground sequestered carbon.

Many organisms aid in pest control in shaded farms. Ants and spiders, for example, reduce damage caused by the coffee berry borer, *Hypothenemus hampei* Ferrari (Perfecto and Vandermeer 2006) and the coffee leaf miner, *Leucoptera coffeella* Guer. (De la Mora et al. 2008). Birds and bats predate on arthropods in shaded coffee plantations. Predation services by birds (Kellermann et al. 2008, Karp et al. 2013) and bats (Williams-Guillén et al. 2008) have been documented to improve coffee yields by 1-14%, amounting to values that exceeded $44–$105/ha/year (Kellermann et al. 2008) and $75-$310/ha/year for farmers (Karp et al. 2013). Pollinators are also critical for coffee production because both commercial species of coffee (*C. arabica* and *C. canephora*) benefit from pollinator visits and pollinator diversity (Klein et al. 2003). In Costa Rica, increased fruit set due to enhanced insect pollination at a per-bush level improved coffee yields by more than 20% in one 1100 ha farm, worth an estimated $62,000 (Ricketts et al. 2004). Again, if 10% of all sun coffee systems were converted to scant or diverse shade, and if pest control services in these shaded systems continued to be valued at $75/ha (Karp et al. 2013), and pollination services at $56/ha (Ricketts et al. 2004), the additional pest-control and pollination contributions provided could exceed $2.3 and $1.7 billion, respectively. Overall, these studies highlight the great potential for increased carbon sequestration, pest-control, and pollination services within shaded coffee systems.

b. Connectivity & resilience to climate change

Shade coffee systems also help to connect forest fragments within the landscape mosaic. For example, migratory birds often use shade coffee farms as a corridor when moving between temperate and tropical regions (e.g., Greenberg et al. 1997). Pollinators such as butterflies (Muriel and Kattan 2009) and native bees (Jha and Dick 2010) can migrate between forest fragments and shade coffee farms. As a result, native trees support pollinators that are critical during the coffee bloom and are able to maintain reproduction and gene flow processes across shade coffee systems (Jha and Dick 2010). Unlike sun coffee systems, which do not provide pollinators with resources throughout the year (Jha and Vandermeer 2010) and are less permeable to dispersing organisms (e.g., Muriel and Kattan 2009), shade coffee farms can promote pollinator populations and serve as corridors for organisms moving regionally between forest fragments.

The importance of connectivity between coffee and protected areas is tremendous given the overlap and proximity of biodiversity hotspots and coffee growing regions (Hardner and Rice 2002) and the importance of shaded coffee in the face of global climate change. Coffee farms are often located adjacent to protected areas, and in many countries, including El Salvador, Guatemala, and Costa Rica, more than 30% of area surrounding coffee regions (50 km radius) fall within protected areas (Jha et al. 2012). Because organisms like birds, bats, and bees in tropical habitats often disperse across short distances, the proximity of coffee farms to protected areas magnifies the role of coffee in serving as an important biological corridor.

Shaded systems have also been identified as part of the remedy for confronting harsh new environments in coffee regions due to climate change (DaMatta and Ramalho 2006). Climatological models predict that the Caribbean and Central America will experience general drying as well as stronger later-season hurricanes (Neelin et al. 2006). Hurricanes can result in major economic losses to coffee farmers but farms with more complex vegetation (i.e. greater tree density and tree species richness) experience significantly fewer post-hurricane landslides (Philpott et al. 2008b). Coffee farmers, realizing enhanced risk in less shaded fields, have engaged in post-hurricane mitigation focused on increasing the planting of more shade trees within their coffee fields (Cruz-Bello et al. 2011). Shaded and diversified coffee farms also provide greater climate regulating services, with potential impacts on coffee berry development and overall yield (Lin et al. 2008)(Table 1). Coffee depends on seasonal rainfall (or irrigation) for flowering and leaf photosynthesis, thus coffee growth rates and yields are highest at specific precipitation and temperature ranges (Lin et al. 2008, and references therein). We spatially quantified the change in coffee suitability in Mesoamerica using the same methodology as described in Läderach et al (2010a) for Nicaragua and Schroth et al (2009) for Chiapas in Mexico. We used (i) WorldClim (http://www.worldclim.org) as the current climate data base, (ii) the most representative Global Climate Models (GCM) of the Fourth Assessment Report (AR4) for the Special Reports on Emission Scenarios (SRES) A2a (business as usual) emission scenario and (iii) existing data of coffee suitability in Central America as input data for the Maxent (Phillips et al 2006) niche model. The Maxent model predicts spatially current climatically suitable coffee growing areas based on presence data and the climate at these locations. The established relation between the current climate and the suitability index are then projected to the future. The model is based on the assumption that in the future the same climatic factors will drive coffee growth as currently, therefore the model does not take into account any adaptation strategies by means of germplasm or other improvements. We show that there is an important decrease in the suitability of coffee-producing areas by 2050 (Fig. 4). Coffee suitability in this context refers to areas that are climatically suitable to grow coffee, where values below zero indicate areas less suitable than current conditions, and values above zero indicate areas more suitable than current conditions. Specifically, the average temperature is predicted to increase by 2-2.5 degrees Celsius by 2050, and because coffee is very sensitive to changes in temperature, coffee planting will need to move up slope by 300-400 m in order to compensate for the increase in temperature (Läderach et al. 2010b). The shift in elevation will increase the pressure on forests and the environmental benefits they provide to downstream communities.

4. Synthesis

Synthesizing research on global coffee distribution and cultivation practices, livelihoods, biodiversity, ecosystem services, and climate resilience, it is clear that distribution and cultivation practices are heterogeneous and are largely a function of local and global market forces, incentives for intensification, and price premiums for diversification or improved livelihoods. Traditional shade systems comprise less than 24% of the coffee areas surveyed in 2010, and the coffee expansion in the past two decades has been typified by intensive non-shaded practices. Millions of coffee farmers continue to struggle for survival despite the production of high quality coffees and the generation of critical ecosystem services (Bacon et al. 2008). While some ecosystem services (ES) are well-known to coffee farmers (Cerdan et al. 2012), many others remain obscure to external agencies due to the indirect nature of their services and the potential for interaction (Bennett et al. 2009). Henry et al. (2009) examined interactions between plant biodiversity, regulating (C sequestration), and provisioning (food production) ecosystem services in Kenya and found that increasing C sequestration by adding more trees could have a negative effect on food production. In another example, Méndez et al. (2009) showed that a higher density and diversity of shade trees resulted in a higher potential for provisioning services (e.g. timber) with greater profits for farmers, but with lower coffee yields. Because coffee yields are typically assessed independent of yield from timber, other crops, or ecosystem services, it may be difficult for governments and conservation institutes to weigh the benefits of diversified farming approaches. We propose three main focal research and development areas that could advance ecosystem service provision and sustainable livelihoods in coffee systems.

a. Improve certification and ecosystem service valuation

While certification is a common default approach used to integrate sustainable agriculture with worker livelihoods, the certification approach is challenged by the limited nature of certifications available and organizational and financial costs for certification. Existing certifications have unique ecological standards, offer distinct economic incentives to different agents (directly to growers, exporters, or to certification agencies), and also differ in the price premium provided (Bacon et al. 2008, Calo and Wise 2005, Raynolds et al. 2007). As a result, farms that provide substantial ecosystem services but do not qualify for existing certifications are left out, and those that do qualify often face high costs of inspection and certification. For example, while Organic and Fair Trade certification may raise coffee export prices (Bacon et al. 2008), these returns may not cover the additional costs associated with maintenance and certification (Calo and Wise 2005).

We suggest research and development efforts in the exploration of a combined certification approach (i.e. both Fair Trade and Organic), which could balance the costs and benefits of different certification systems (Calo and Wise 2005, Philpott et al. 2007). Because certification can be expensive, multiple certifications may be cost-prohibitive, especially for smallholder farmers (Calo and Wise 2005), but discounts or incentives could be put into place in order to minimize the costs of multiple certifications. Alternatively, government agencies could subsidize or provide loans for the initial costs of certification and transition, or these expenses could be paid after the first years of profit are earned. In this way and others, the certification system could be revised to be more inclusive of small landholders. It is also essential that certification studies incorporate an analysis of the time, labor, and economic costs involved. Future work should explicitly investigate the support needed from financial, institutional, and community agencies in order to successfully transition non-certified farmers to Organic, Fair Trade, biodiversity- or livelihood- friendly coffees.

b. Diversify coffee farms

For both economic and ecological resiliency, the diversification of crops and livelihoods is essential for coffee producers (Rice 2008). This review describes how a diverse array of crops and shade trees provides farmers with 1) alternative income sources in cases of crop losses and price fluctuations, 2) income across the growing season, 3) food for home consumption, and 4) improved fertilization, erosion control, and habitat for pollinators and predators. Thus, it is essential to evaluate the services and products provided by shade trees and additional crops in addition to coffee yields when evaluating diversified farming approaches. An additional level of diversity worth incorporating is the selection and sharing of heirloom and local seed (especially corn, beans, rice and other subsistence crops), including local landraces which could be resistant to extreme weather and changing precipitation patterns (Méndez et al. 2010a). These diversified farming practices require involvement of civil society and the state in order to address the structural drivers affecting persistent hunger, fraying rural safety nets for health, and educational opportunities (Bacon et al. 2008).

c. Change local and global policy

Since 1989, the role of national governments directly influencing global coffee markets and prices paid to producers (through the ICA) has decreased (Topik et al. 2010) and in these years, in many regions, rural poverty rates have increased together with accelerating rates of environmental destruction (Bacon et al 2008). We suggest that national governments of coffee producing regions need to play a more active role in providing basic services to their populace and protecting ecosystem services. Payments or Compensation for Ecosystem Services (PES) provide one avenue for compensation or rewards from the beneficiaries directly to the landholders and have been implemented in a number of nations, including Costa Rica, Mexico, and China (reviewed in Engel et al. 2008). Rewards for ecosystem services should not be used to directly regulate land management, but they could provide valuable incentives, especially with the incorporation of management extension services (Engel et al. 2008, van Noordwijk and Leimona 2010). The difficulties of quantifying PES or integrating them with the practices of potential stakeholders or government agencies create real challenges (van Noordwijk and Leimona 2010). Thus, successful programs require stakeholder involvement and development of sustainable farmer livelihoods (van Noordwijk and Leimona 2010). Local, regional, and even national cooperatives with administrative capacity and accountability to their membership can leverage international development funding to improve coffee yields and quality, increase production from the diversified shade canopy, and support a wide array of social development projects (Raynolds et al. 2007). Incentives and infrastructure directed toward farmers who use sustainable practices and preserve biodiversity could encourage producers to make a living while being good stewards of the land.

8. Conclusions

Our findings show that while global coffee acreage has decreased since 1990, cultivation has grown dramatically in Asia and has been accompanied by declining levels of diverse shade coffee, thus threatening the availability and flow of ecosystem services across the globe. Although there have been several gains in the growth of sustainable certifications, research also suggests that livelihoods remain vulnerable and poverty and hunger are persistent in many farming communities. Research in coffee systems has allowed for an improved understanding of habitat management and biodiversity, a closer examination of relationships between biodiversity and ecosystem services, and a greater understanding of tropical spatial ecology and connectivity. Coffee has also emerged as an important test case for assessing the effects of different certification programs, evaluating the links between local and global economies, and examining the arena for participatory and interdisciplinary research. However, diversified efforts are needed to develop effective solutions for sustainable livelihoods, and it is essential that all members in the coffee value chain become active stakeholders in these efforts. From local to global scales, it is clear that farmers, cooperatives, government agencies, and consumers all influence coffee land management and rural livelihoods. We document that many of the landscapes that generate important ecosystem services do not necessarily harvest the benefits in terms of income, incentives, and opportunities. In order for coffee landscapes to be sustainable for humans and their ecosystems, we need to 1) better incorporate human well-being and livelihoods into global concepts of sustainability, 2) encourage the diversification of coffee farms to promote greater resilience to changes in global markets and climates, and 3) improve the valuation and reward for ecosystem services via certification and other systems in order to compensate farmers for the innumerable services that shaded landscapes provide. Building synergistic and cooperative relationships between farmers, certifiers, global agencies, researchers, and consumers, can provide greater transparency and creative solutions for promoting ecological processes and well-being across global coffee systems.

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References

Aide TM, Grau HR. 2004. Ecology - Globalization, migration, and Latin American ecosystems. Science 305: 1915-1916.

Arnould EJ, Plastina A, Ball D. 2009. Does Fair Trade Deliver on Its Core Value Proposition? Effects on Income, Educational Attainment, and Health in Three Countries. Journal of Public Policy & Marketing 28: 186-201.

Avelino J, Zelaya H, Merlo A, Pineda A, Ordonez M, Savary S. 2006. The intensity of a coffee rust epidemic is dependent on production situations. Ecological Modelling 197: 431-447.

Avelino J, Cabut S, Barboza B, Barquero M, Alfaro R, Esquivel C, Durand JF, Cilas C. 2007. Topography and crop management are key factors for the development of American leaf spot epidemics on coffee in Costa Rica. Phytopathology 97: 1532-1542.

Babbin N. 2010. Dissertation: Agrarian Change, Agroecological Transformation and the Coffee Crisis in Costa Rica. University of California, Santa Cruz.

Bacon C, Méndez V, Gliessman S, Goodman D, Fox J. 2008. Confronting the coffee crisis : fair trade, sustainable livelihoods and ecosystems in Mexico and Central America. Cambridge, Mass.: MIT Press.

Bacon CM. 2010. Who decides what is fair in fair trade? The agri-environmental governance of standards, access, and price. Journal of Peasant Studies 37: 111-147.

Beenhouwer M, Aertsb R, Honnaya O. 2013. A global meta-analysis of the biodiversity and ecosystem service benefits of coffee and cacao agroforestry. Agriculture, Ecosystems and Environment 175.

Beer J, Muschler R, Kass D, Somarriba E. 1998. Shade management in coffee and cacao plantations. Agroforestry Systems 38: 139-164.

Bennett E, Peterson G, Gordon L. 2009. Understanding relationships among multiple ecosystem services. Ecology Letters 12: 1-11.

Bhagwat SA, Kushalappa CG, Williams PH, Brown ND. 2005. Landscape approach to biodiversity conservation of sacred groves in the Western Ghats of India. Conservation Biology 19: 1853-1862.

Bosselmann AS. 2012. Mediating factors of land use change among coffee farmers in a biological corridor. Ecological Economics 80: 79-88.

Bosselmann AS, Dons K, Oberthur T, Olsen CS, Raebild A, Usma H. 2009. The influence of shade trees on coffee quality in small holder coffee agroforestry systems in Southern Colombia. Agriculture Ecosystems & Environment 129: 253-260.

Calo M, Wise TA. 2005. Revaluing Peasant Coffee Production: Organic and Fair Trade Markets in Mexico. Medford, Massachusetts: Global Development and Environment Institute.

CEPAL. 2002. Globalización y desarrollo. Santiago, Chile.

Cerdan CR, Rebolledo MC, Soto G, Rapidel B, Sinclair FL. 2012. Local knowledge of impacts of tree cover on ecosystem services in smallholder coffee production systems. Agricultural Systems 110: 119-130.

Croce M. 2013. Personal Interview. Interviewed by Robert Rice, November 2013.

Cruz-Bello GM, Eakin H, Morales H, Barrera JF. 2011. Linking multi-temproal analysis and community consultation to evaluate the response to the impact of Hurricane Stan in coffee areas of Chiapas, Mexico. Natural Hazards 58.

D'haeze D, Deckers J, Raes D, Phong TA, Loi HV. 2005. Environmental and socio-ecnonomic impacts of institutional reforms on the agricultural sector of Vietnam Land suitability assessment for Robusta coffee in the Dak Gan region. Agriculture, Ecosystems & Environment 105:59-76.

DaMatta F, Ramalho J. 2006. Impacts of drought and temperature stress on cofeee physiology and production: a review. Brazilian Journal of Plant Physiology 18: 55-81.

De Beenhouwera M, Aertsb R, Honnay O. 2013. A global meta-analysis of the biodiversity and ecosystem service benefits of coffee and cacao agroforestry. Agriculture, Ecosystems and Environment: 1-7.

De la Mora A, Livingston G, Philpott SM. 2008. Arboreal Ant Abundance and Leaf Miner Damage in Coffee Agroecosystems in Mexico. Biotropica 40: 742-746.

Donald PF. 2004. Biodiversity impacts of some agricultural commodity production systems. Conservation Biology 18: 17-37.

Engel S, Pagiola S, Wunder S. 2008. Designing payments for environmental services in theory and practice: An overview of the issues. Ecological Economics 65: 663-674.

FAO. 2010. Food and Agriculture Organization. http://faostat.fao.org/site/567/DesktopDefault.aspx?PageID=567#ancor

FAO. 2012. Key differences between Arabica and Robusta coffee. Adapted from International Coffee Organization, www.ico.org.

GAIN Report. 2013. Situation Update—Coffee Rust in Mexico. USDA Foreign Agricultural Service, Report No. MX3015, 4 pp.

Giovannucci D, Potts J, Killian B, Wunderlich C, Soto G, Schuller S, Pinard F, Schroeder K, Vagneron I. 2008. Seeking Sustainability: COSA Preliminary Analysis of Sustainability Initiatives in the Coffee Sector (October 5, 2008), Committee on Sustainability Assessment.

Greenberg R, Bichier P, Angon AC, Reitsma R. 1997. Bird populations in shade and sun coffee plantations in Central Guatemala. Conservation Biology 11: 448-459.

Guadarrama-Zugasti C. 2008. A grower typology approach to assessing the environmental impact of coffee farming in Veracruz, Mexico. Pages 127-154 in Bacon CM, Méndez VE, Gliessman SR, Goodman D, Fox JA, eds. Confronting the coffee crisis: Fair Trade, sustainable livelihoods and ecosystems in Mexico and Central America. Cambridge, MA: MIT Press.

Guhl A. 2004. Coffee and landcover changes in the Colombian Coffee region landscape 1970-1997. Bogota, Colombia: Ensayos.

Guingato P, Nardone E, Notarnicola L. 2008. Environmental and socio-economic effects of intensive agriculture: the Vietnam case. Journal of commodity sicence, technology, and quality 47:135-151.

Hardner J, Rice R. 2002. Rethinking green consumerism. Scientific American 286: 88-95.

ICO. 2013. International Coffee Organization website: http://www.ico.org/botanical.aspIlly E. 2002. The Complexity of Coffee. Scientific American: 86-91.

ITC. 2011. The Coffee Exporter's Guide. International Trade Center. Geneva, Switzerland 248 pp.

Izada F. 2013. Personal Interview. Interviewed by Robert Rice, November 2013.

Jena PR, Chichaibelu BB, Stellmacher T, Grote U. 2012. The impact of coffee certification on small-scale producers' livelihoods: a case study from the Jimma Zone, Ethiopia. Agricultural Economics 43: 429-440.

Jha S, Vandermeer J. 2010. Impacts of coffee agroforestry management on tropical bee communities. Biological Conservation 143: 1423-1431.

Jha S, Dick CW. 2010. Native bees facilitate gene flow across shade coffee landscapes. Proceedings of the National Academy of the Sciences 107: 13760-13764.

Jha S, Bacon C, Philpott SM, Rice RA, Méndez VE, Läderach P. 2012. Shade coffee at a crossroads again: A global review of ecosystem services and farmer livelihoods. Pages 141-208 in Campbell WB, Lopez Ortiz S, eds. Integrating Agriculture, Conservation and Ecotourism: Examples from the Field. Netherlands: Springer.

JNC. 2013. Programa nacional para la renovación de la caficultura. Junta Nacional del Café, Lima, Peru. 15 pp.

Henry M, Tittonell P, Manlay RJ, Bernoux M, Albrecht A, Vanlauwe B. 2009. Biodiversity, carbon stocks and sequestration potential in aboveground biomass in smallholder farming systems of western Kenya. Agriculture Ecosystems & Environment 129: 238-252.

Kellermann J, Johnson M, Stercho A, Hackett S. 2008. Ecological and economic services provided by birds on Jamaican Blue Mountain coffee farms. 22: 1177-1185.

Klein AM, Steffan-Dewenter I, Tscharntke T. 2003. Fruit set of highland coffee increases with the diversity of pollinating bees. Proceedings of the Royal Society of London Series B-Biological Sciences 270: 955-961.

P, Oberthür T, Niederhauser N, Usma H, Collet L, Pohlan J. 2006. Café Especial: Factores, dimensiones e interacciones Pages 141-160 in Pohlan J, Soto L, Barrera J, eds. El cafetal del futuro: Realidades y Visiones. Aachen: Shaker Verlag.

Läderach P, Lundy M, Jarvis A, Ramírez J, Pérez PE, Schepp K, Eitzinger A (2010a) Predicted impact of climate change on coffee-supply chains. *In* Leal Filho, W. (ed) The Economic, social and Political Elements of Climate Change, Springer Verlag, Berlin, DE. 19 p.

Läderach P, Haggar J, Lau C, Eitzinger A, Ovalle O, Baca M, Jarvis A, Lundy M. 2010b. Mesoamerican coffee: Building a climate change adaptation strategy. CIAT Policy Brief no. 2. Cali, Colombia: Centro Internacional de Agricultura Tropical.

Lin B, Perfecto I, Vandermeer J. 2008. Synergies between agricultural intensification and climate change could create surprising vulnerabilities for crops. BioScience 58: 847-854.

Lopez-Bravo DF, Virginio ED, & Avelino J. 2012. Shade is conducive to coffee rust as compared to full sun exposure under standardized fruit load conditions. Crop Protection, 38, 21-29.

Méndez V, Gliessman S, Gilbert G. 2007. Tree biodiversity in farmer cooperatives of a shade coffee landscape in western El Salvador. Agriculture Ecosystems & Environment 119: 145-159.

Méndez V, Shapiro E, Gilbert G. 2009. Cooperative management and its effects on shade tree diversity, soil properties and ecosystem services of coffee plantations in western El Salvador. Agroforestry Systems 76: 111-126.

Méndez VE, Bacon CM, Olson M, Morris KS, Shattuck AK. 2010a. Agrobiodiversity and shade coffee smallholder livelihoods: A review and synthesis of ten years of research in Central America. Professional Geographer 62: 357-376.

Méndez VE, Bacon C, Olson M, Petchers S, Herrador D, Carranza C, Trujillo L, Guadarrama-Zugasti C, Cordón A, Mendoza A. 2010b. Effects of Fair Trade and organic certifications on small-scale coffee farmer households in Central America and Mexico. Renewable Agriculture and Food Systems 25: 236-251.

Moguel P, Toledo VM. 1999. Biodiversity conservation in traditional coffee systems of Mexico. Conservation Biology 13: 11-21.

Montagnon C, Marraccini P, Bertrand B. 2012. Specialty coffee: managing quality. International Plant Nutrition Institute, Southeast Asia Program (IPNI-SEAP): Penang Malaysia. Pages 93-122 in Oberthür T, Läderach P, Jürgen HA, Cook JH, eds. Breeding for coffee quality.

Muriel SB, Kattan GH. 2009. Effects of Patch Size and Type of Coffee Matrix on Ithomiine Butterfly Diversity and Dispersal in Cloud-Forest Fragments. Conservation Biology 23: 948-956.

Muschler R. 2001. Shade improves coffee quality in a sub-optimal coffee-zone of Costa Rica. Agroforestry Systems 51: 131 – 139.

Neelin JD, Munnich M, Su H, Meyerson JE, Holloway CE. 2006. Tropical drying trends in global warming models and observations. Proceedings of the National Academy of Sciences of the United States of America 103: 6110-6115.

Neilson J. 2008. Global private regulation and value-chain restructuring in Indonesian smallholder coffee systems. World Development 36: 1607-1622.

O’Brien TG, Kinnaird MF. 2003. Caffeine and conservation. Science: 587.

Oxfam. 2002. Mugged: Poverty in Your Coffee Cup.

Palm C, et al. 2005. Carbon losses and sequestration after land use change in the humid tropics. Pages 41-63. Slash-and-Burn Agriculture: the Search for Alternatives. New York: Columbia University Press.

Perfecto I, Vandermeer J. 2006. The effect of an ant-hemipteran mutualism on the coffee berry borer (*Hypothenemus hampei*) in southern Mexico. Agriculture Ecosystems & Environment 117: 218-221.

Perfecto I, Rice RA, Greenberg R, VanderVoort ME. 1996. Shade coffee: A disappearing refuge for biodiversity. Bioscience 46: 598-608.

Phillips SJ, Anderson RP, Schapire RE (2006) Maximum entropy modeling of species geographic distributions. Ecological Modelling 190:231-259.

Philpott SM, Bichier P, Rice R, Greenberg R. 2007. Field-testing ecological and economic benefits of coffee certification programs. Conservation Biology 21: 975-985.

Philpott SM, Arendt W, Armbrecht I, Bichier P, Dietsch T, Gordon C, Greenberg R, Perfecto I, Soto-Pinto L, Tejeda-Cruz C, Williams G, Valenzuela J. 2008a. Biodiversity loss in Latin American coffee landscapes: reviewing evidence on ants, birds, and trees. Conservation Biology 22: 1093-1105.

Philpott SM, Lin BB, Jha S, Brines SJ. 2008b. A multi-scale assessment of hurricane impacts on agricultural landscapes based on land use and topographic features. Agriculture Ecosystems & Environment 128: 12-20.

Raynolds LT, Murray D, Heller A. 2007. Regulating sustainability in the coffee sector: A comparative analysis of third-party environmental and social certification initiatives. Agriculture and Human Values 24: 147-163.

Rice P, McLean J. 1999. Sustainable coffee at the crossroads. Consumer's Choice Council. Report no.

Rice RA. 2008. Agricultural intensification within agroforestry: The case of coffee and wood products. Agriculture Ecosystems & Environment 128: 212-218.

Ricketts TH, Daily GC, Ehrlich PR, Michener CD. 2004. Economic value of tropical forest to coffee production. Proceedings of the National Academy of Sciences of the United States of America 101: 12579-12582.

Rueda X, Lambin E. 2013. Linking Globalization to Local Land Uses: How Eco-consumers and Gourmands are Changing the Colombian Coffee Landscapes. World Development 41: 286-301.

SCAA. 2012. Specialty Coffee Facts and Figures. Report. Specialty Coffee Association of America. Long Beach, CA. Long Beach, CA. Report no.

Soto-Pinto L, Perfecto I, Caballero-Nieto J. 2002. Shade over coffee: its effects on berry borer, leaf rust and spontaneous herbs in Chiapas, Mexico. Agroforestry Systems 55: 37-45.

Soto-Pinto L, Perfecto I, Castillo-Hernandez J, Caballero-Nieto J. 2000. Shade effect on coffee production at the northern Tzeltal zone of the state of Chiapas, Mexico. Agriculture, Ecosystems and Environment 80: 61-69.

Soto-Pinto L, Anzueto M, Mendoza J, Ferrer GJ, de Jong B. 2010. Carbon sequestration through agroforestry in indigenous communities of Chiapas, Mexico. Agroforestry Systems 78: 39-51.

Schroth G, Laderach P, Dempewolf J, Philpott S, Haggar J, Eakin H, Castillejos T, Moreno

JG, Soto Pinto L, Hernandez R, Eitzinger A, Ramirez-Villegas J (2009) Towards a climate change adaptation strategy for coffee communities and ecosystems in the Sierra Madre de Chiapas, Mexico. Mitig Adapt Strateg Glob Change 14:605–625

Staver C, Guharay F, Monterroso D, Muschler RG. 2001. Designing pest-suppressive multistrata perennial crop systems: shade-grown coffee in Central America. Agroforestry Systems 53: 151-170.

Topik S, Talbot J, Samper M. 2010. Introduction Globalization, Neoliberalism, and the Latin American Coffee Societies. Latin American Perspectives 171: 5-20.

Tscharntke T, et al. 2011. Multifunctional shade-tree management in tropical agroforestry landscapes - a review. Journal of Applied Ecology 48: 619-629.

Ukers W. 1922. All About Coffee. New York: The Tea and Coffee Trade Journal Company.

van Noordwijk M, Leimona B. 2010. Principles for Fairness and Efficiency in Enhancing Environmental Services in Asia: Payments, Compensation, or Co-Investment? Ecology and Society 15.

Virginio EM. 2013. Impactos de la roya en Centroamérica y avances de los

planes de control en los países: actualización con base en talleres nacionales. Published on CATIE website: http://biblioteca.catie.ac.cr/royadelcafeto/

Wardle DA, Bardgett RD, Callaway RM, Van der Putten WH. 2011. Terrestrial Ecosystem Responses to Species Gains and Losses. Science 332: 1273-1277.

Wilson K. 1999. Coffee, cocoa and tea. Wallingford, Oxon, UK: CABI Publishing.

Zeltzer N. 2008. Foreign-Economic-Retirement Migration: Promises and Potential, Barriers and Burdens Elder Law Journal. 16: 211- 241.

Table and Figure Captions:

Fig. 1. Spatial distribution of global coffee cultivation.

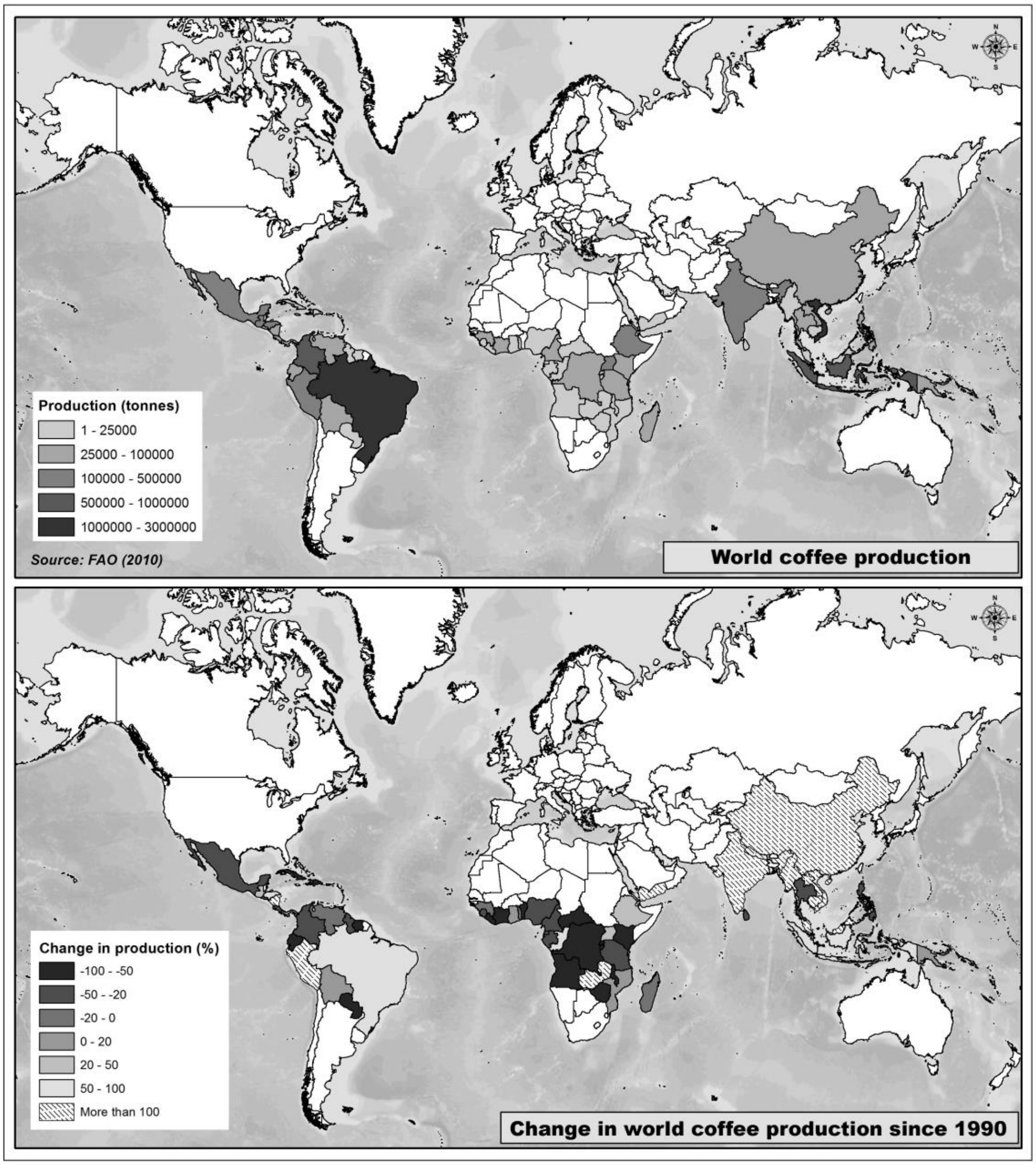

Fig. 2. Percent coffee area managed beneath different technological/shade levels. Diverse shade has a closed or nearly closed canopy (>40% cover) with 10 or more species of shade trees, Scant shade has minimal but existing canopy (1-40% cover) and usually 1-2 species of shade trees (all with <10 species), and Sun coffee has no shade or shade trees in the production area.

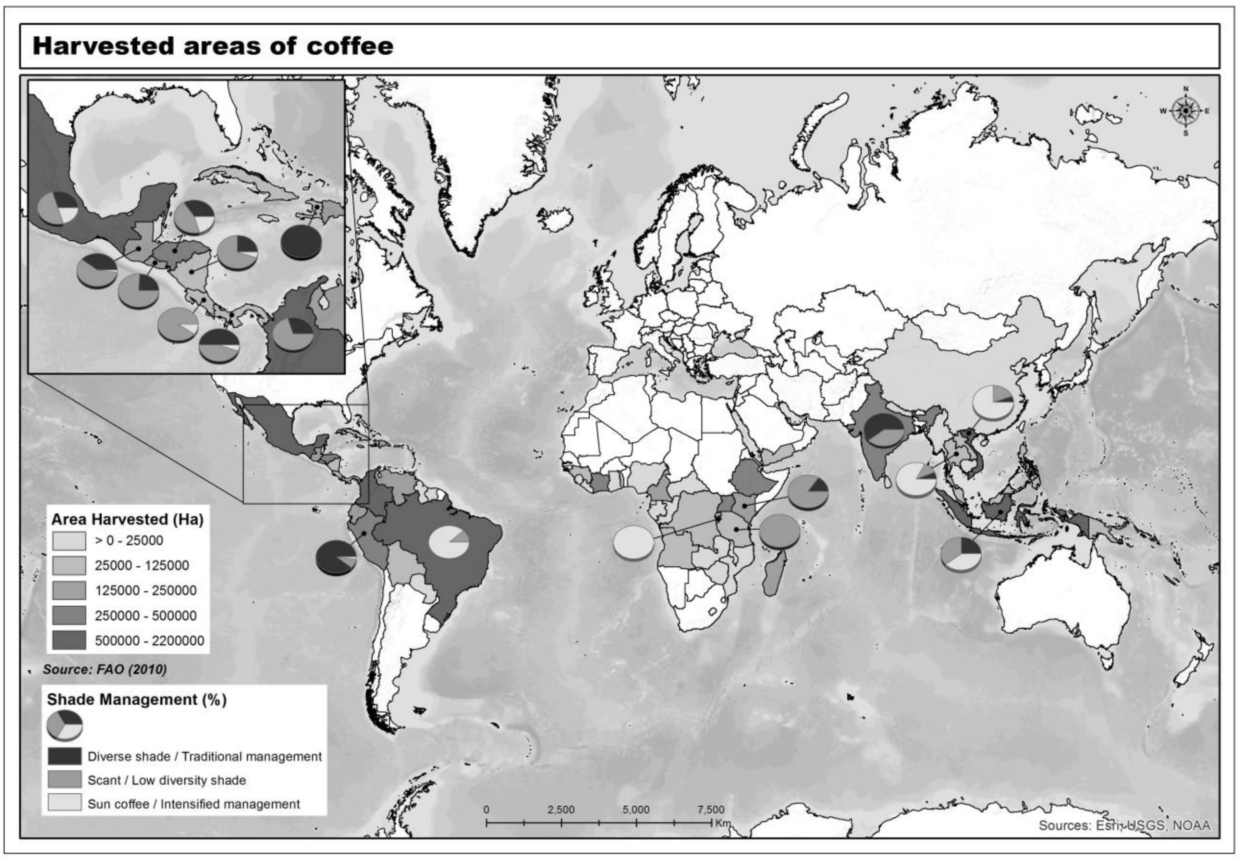

Fig. 3. Dollar size of the specialty coffee market in Billions.

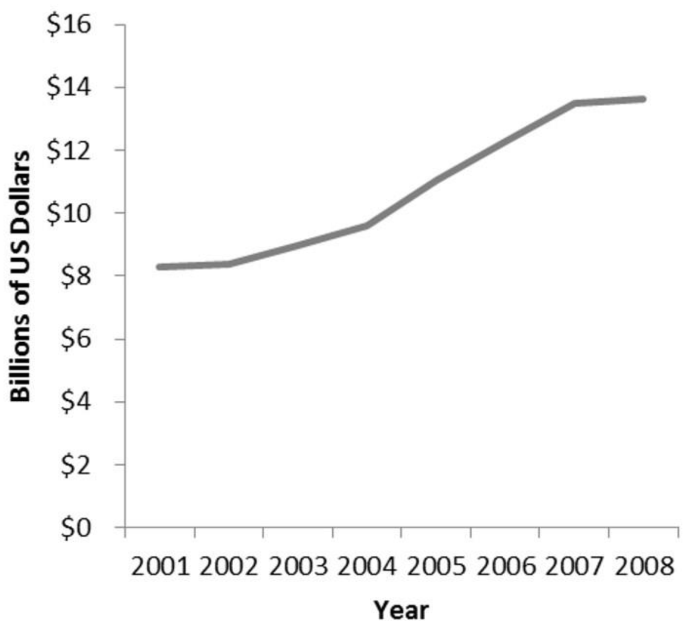

Fig. 4. Distribution of coffee suitability in 2050 and current protected areas in Mesoamerica.

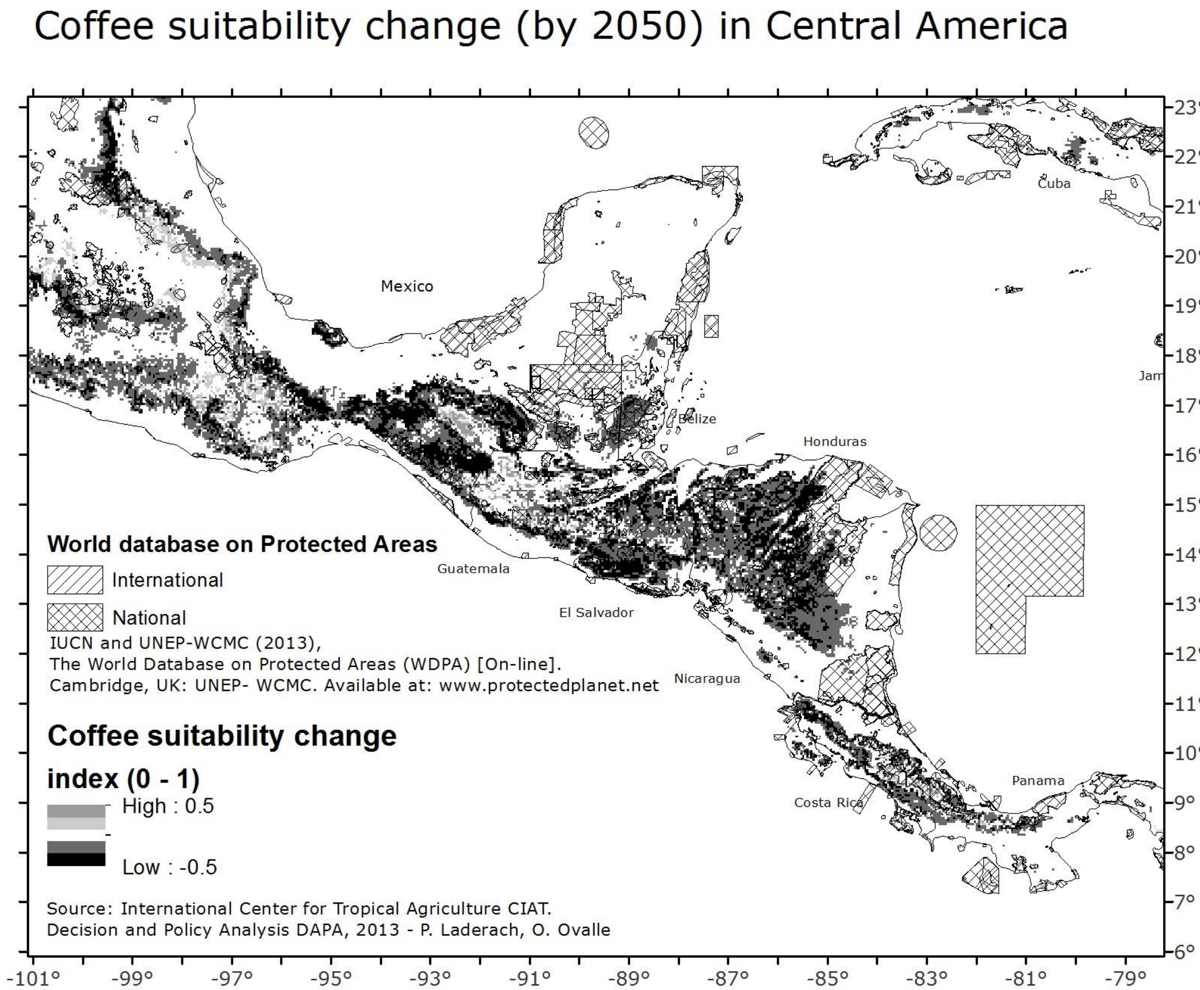

Table 1. Impact of increasing vegetation complexity of shade coffee on pollination, pest-control, climate-regulation, and nutrient & sequestration ecosystem services (description of literature and references in Table S2).

pollination	**pest control**	**climate regulation**	**nutrient & sequestration**
+ higher pollinator species richness [1, 2] + higher pollinator abundance [2, 4] + higher native bee abundance, higher social bee abundance [3] 0 no impact on pollinator abundance [5] 0 no impact on pollinator diversity [68] – lower pollinator abundance [6, 68] – lower pollinator species richness [68]	+ higher parasitism [49] + higher predator abundance [8, 9, 14, 16, 17, 42, 55, 56, 57, 59, 67] + higher predator nest availability [11] + higher predator species richness [9, 15, 42, 43, 55, 67] + higher removal of pests [7, 12, 13, 44, 46, 47, 53, 58] + lower pest abundance [10, 13, 48, 51, 52, 61, 62, 63, 64] + lower pest damage [66] 0 no impact on pest abundance [61, 62, 63] 0 no impact on predator abundance [15, 16, 18, 49, 64, 65] 0 no impact on predator species richness [49, 54] 0 no impact on prey abundance [50] 0 no impact on removal of pests [42, 43, 45] – higher pest abundance [19, 20, 21, 22, 51, 53] – higher pest species richness [60] – lower predator abundance [17, 65] – lower predator species richness [57]	+ higher leaf wetness frequency [19] + lower air, soil, or leaf temperatures (mean maximum or mean) [23, 25, 27, 28, 29, 30, 33] + lower global, PAR, or net solar radiation [23, 25, 28, 30, 33] + fewer and smaller landslides [24] + lower wind speed [25, 28, 30] + lower soil evaporation rates, lower plant evaporative transpiration [26] + higher relative extractable water in soil, higher soil moisture [29, 31, 33] + higher precipitation capture [31] + lower humidity and solar radiation fluctuations [32] + lower frost damage [34] + lower intra-day fluctuations in temperature, lower rate of cooling of night air [19, 32, 33]	+ higher above ground carbon storage [35, 38, 39, 69] + higher total soil organic C [27, 69] + higher N mineralization, lower NP nutrient excess (inputs minus outputs) [27, 36, 41] + higher soil microbial activity [27] + higher soil pH, CEC, Ca, and Mg, and lower K [37] + higher N concentration in leaves [38] + higher fractions of P available to agricultural crops [40] 0 no impact on soil organic carbon [70]