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 crucial 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. Although overall cultivated coffee area has decreased by 8% since 1990, coffee production and agricultural intensification have 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 greater in shaded coffee farms, but many coffee-growing regions are removing shade trees from their management. Although it is clear that there are ecological and socioeconomic 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 each year (Illy 2002). Coffee is among the most valuable legally traded commodities from the developing world (FAO 2014), engaging between 14 million 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 (or simply *shade*) coffee farms for biodiversity conservation and ecosystem service provision has gained widespread attention from the public and scientific communities (Perfecto et al. 1996, Tscharntke et al. 2011, Jha et al. 2012, De Beenhouwer et al. 2013). 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 article, 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.

Shifting global production patterns and management practices

The two coffee species of commercial value, *Coffea arabica* and *Coffea canephora* (robusta), both originate from Africa; the former has generally preferred taste qualities, and the latter exhibits higher yield and pest resistance (ITC 2012, *www.ico.org/botanical.asp*). *Coffea arabica* dominates global coffee landscapes, accounting for 60% of the total coffee volume produced (ITC 2012). Although 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; by the 1970s, coffee's cultivation dominated more than 8.8 million hectares (ha) of tropical landscapes. Between 1970 and 1990, the global coffee area and average yields increased by 25% (8.8 million to 11.1 million ha and 433 to 543 kilograms [kg] per ha, respectively), and global production increased by 58% (FAO 2014). Interestingly, although the global area decreased to 10.2 million ha between 1990 and 2010 (the year with the most recent comprehensive data), production still climbed 36%, which is evidence of an overall intensification in several key countries (e.g., Brazil and Colombia), coffee abandonment in others (e.g., Burundi and Kenya), and the rapid expansion of high-yield coffee in new countries (e.g., Vietnam and Indonesia; FAO 2014). 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 resulted in an 89% yield increase over that period (FAO 2014), and recognition from coffee experts that production there has been highly industrialized (Marco Croce, Fazenda Ambiental Fortaleza, Mococa, Brazil, personal communication, 20 November 2013; Felipe Izada, Coffee Resources, Miami, Florida, personal communication, 21 November

BioScience 64: 416–428.
doi:10.1093/biosci/biu038 Advance Access publication 16 April 2014

2013). Since the mid-1980s, 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 2012). Robusta yields there soared from a historical average of 450 kg per ha prior to the 1950s to 1558 kg per ha by 2004 (D'haeze et al. 2005), more than double the global yield average at the time, which reveals 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 practices.

A closer look reveals that the shift in production between 1990 and 2010 was regional: 45% of the nations exhibiting decreases were in Africa, whereas Asian countries accounted for 35% of those with increased production (figure 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 produced in 2010. In Vietnam alone, the cultivated area increased by 731%, yields by 45%, and the total production by 1102% between 1990 and 2010 (figure 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 2014).

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 (O'Brien and Kinnaird 2003, D'haeze et al. 2005, FAO 2014). In contrast, in places where the coffee area has declined, such as Costa Rica and Ecuador, the expansion of high-yield agriculture has caused a decrease in coffee prices, which has, in turn, resulted in the abandonment of marginal agricultural lands (Aide and Grau 2004, FAO 2014) in combination with increased land prices due to urbanization. The result is an increase in global production despite decreases in the overall coffee area (figure 1). Higher land values due to exurbanization 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 before 1995, Colombia), but sustained global prices after 2005 have spurred 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, such as 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 less than 10 ha of coffee (reviewed in Jha et al. 2012), as has been documented in Asia (e.g., Jena et al. 2012) and in Africa (e.g., Neilson 2008). 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 the number of coffee bushes instead of in ha (e.g., 300 coffee bushes), whereas in many Mesoamerican smallholder farms, stand densities are as high as 6700 coffee bushes per ha (Méndez et al. 2007). These patterns in farm size tend to shift, depending on coffee prices and government incentives, as is evidenced in Latin America, where a decrease in the number of large estates and an increase in the number of smallholders and microproducers 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, whereas the proportion of pasture land increased from 31% to 50%, largely because of basement-level international coffee prices (Babin 2010). This example highlights the need for locally and regionally specific research into the social–ecological causes and consequences of changing coffee production patterns.

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, the density of bushes, the presence of additional wild or cultivated plants, the age of bushes and pruning style, and agrochemical use (Moguel and Toledo 1999, Tscharntke et al. 2011). The most traditional coffee-growing practices, as seen in rustic coffee, involve 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 an increased use of synthetic agrochemicals (e.g., pesticides, fungicides, herbicides, 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 coverage are region specific. In Latin America, between 1970 and 1990, nearly 50% of shade coffee farms were converted to low-shade systems (Perfecto et al. 1996). The 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, remain largely devoid of diverse-shade systems and have either maintained or increased their

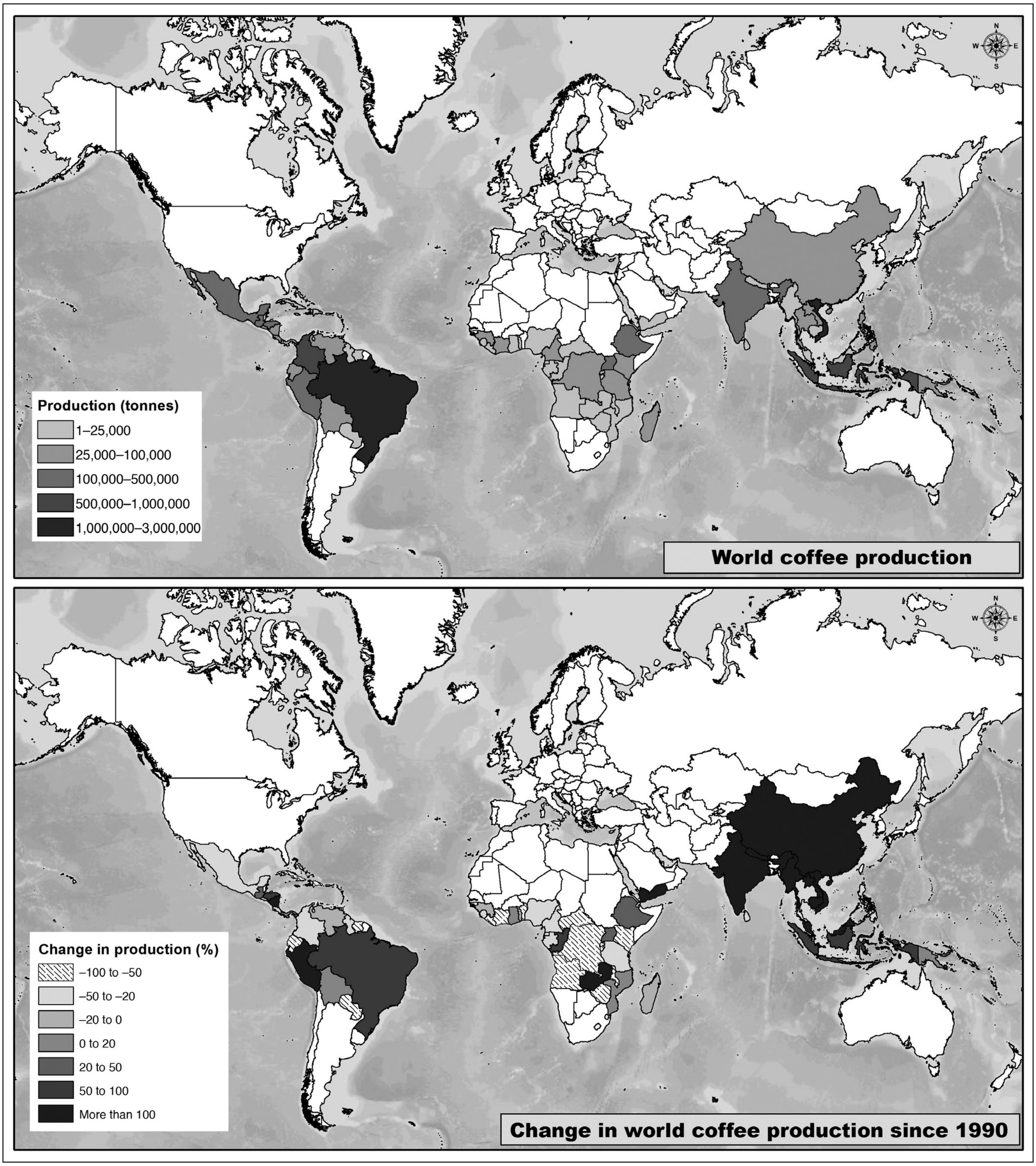

Figure 1. Distribution of global coffee cultivation. Source: The data are from the 2010 data set from FAO (2014).

areas of sun coffee (Guhl 2004; Marco Croce, Fazenda Ambiental Fortaleza, Mococa, Brazil, personal communication, 20 November 2013). From the 1990s to 2010, most Latin American countries decreased the percentage of total coffee production area dedicated to traditional diversified shade coffee production but at a slower rate than from 1970 to the 1990s. On the basis of the nine countries for which we have data from both the 1990s and the 2010s, we found that more than half of these countries experienced a decrease in the percentage of coffee under traditional shade management (Colombia, Costa Rica, El Salvador, Guatemala, and Nicaragua). However, because coffee production areas

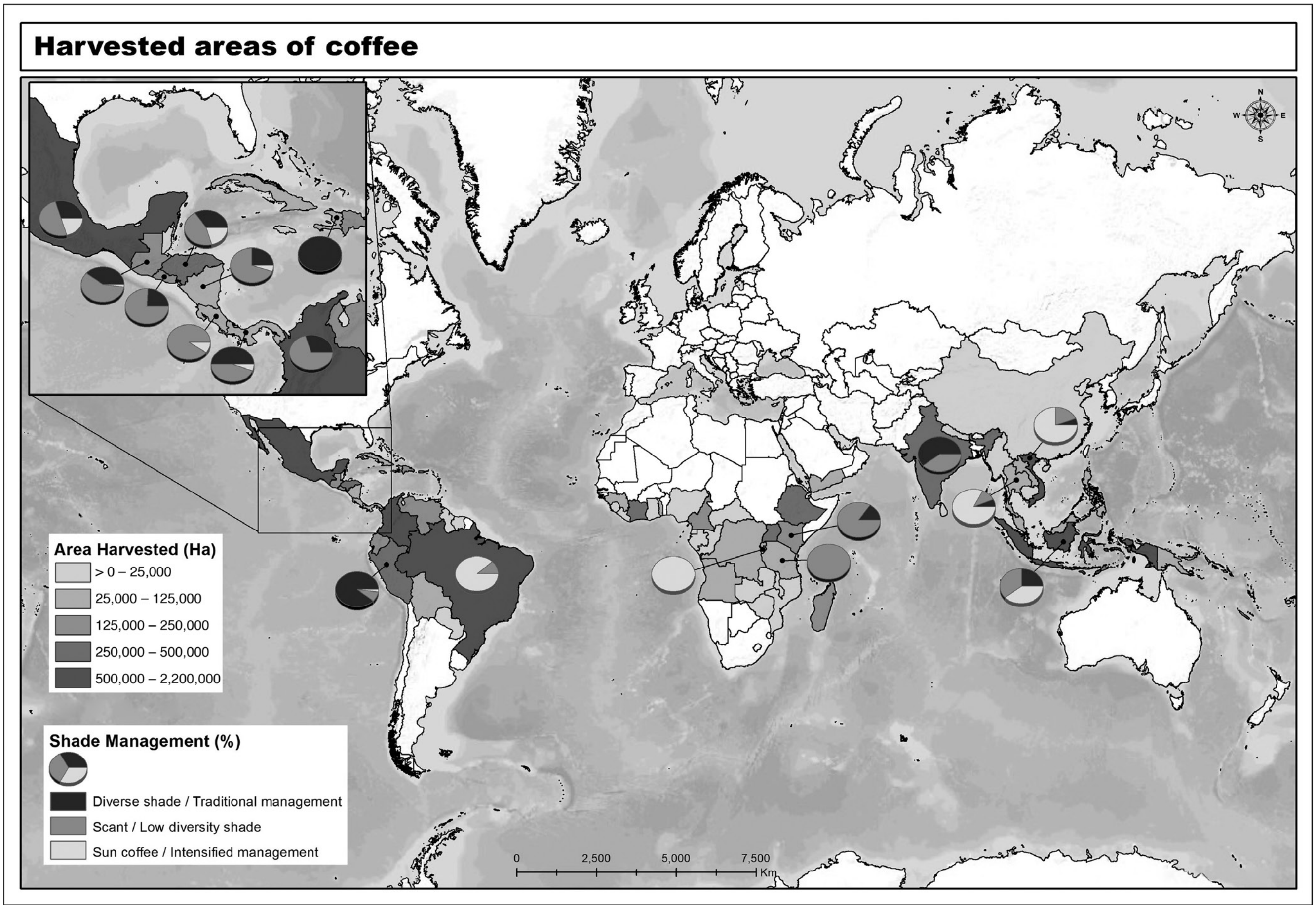

Figure 2. Percentage (%) of the cultivated coffee area managed under different technology or shade levels.* Diverse shade *has a closed or nearly closed canopy (more than 40% cover), with 10 or more species of shade trees.* Scant shade *has a minimal but existing canopy (1%–40% cover) and usually 1 or 2 species of shade trees (all with fewer than 10 species).* Sun coffee *has no shade or shade trees in the production area. Abbreviations: ha, hectares; km, kilometers. Source: The data are from the 2010 data set from FAO (2014).

expanded in the remaining four countries and because these countries (Honduras, Panama, Mexico, Haiti) reported higher percentages of shade production, our calculations for Latin America suggest an increase in the area of land dedicated to diverse shade.

However, a wider comparison of 19 countries for which we have 2010 data shows that 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 (figure 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 (figure 2).

Coffee vegetation management patterns are nuanced and often depend on farm size, available alternatives, national and regional politics, risk-avoidance strategies, and development funding. For example, 81% of the coffee in Nicaragua and El Salvador grew under a shade canopy in 1996, and although recent surveys document declines in shade tree diversity since then, these declines mostly occurred on larger farms; in contrast, many smallholder cooperatives preserve high levels of biodiversity, including more than 100 species of shade trees on fewer 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).

Although 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) socioeconomic 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 of these five major factors and document the evidence supporting and contradicting each.

(1) Cultivar origin. The two globally dominant coffee species are *C. arabica* (arabica) and *C. canephora* (robusta), which have distinct origins and cultivation histories and therefore differ in flavor, ideal growing conditions, resistance to pests and pathogens, and yield, among other traits. Although arabica and its cultivars grow best at middle to high elevations (600–2000 meters [m]), exhibiting their maximum photosynthetic rate at moderate temperatures and higher shade levels, robusta and its cultivars are tolerant of lower elevation (up to 800 m) and full sun exposure and grow best at temperatures between 24 and 30 degrees Celsius (Wilson 1999). The distinctions between these species—their tolerance for temperature shifts, the development of disease resistant cultivars, and a number of socioeconomic factors described in this review—underlie much of the variations in current coffee vegetation management practices seen across the globe.

(2) Coffee diseases and yield. Fungi cause most major coffee diseases (e.g., coffee leaf rust, brown eyespot, coffee berry disease) and primarily affect *C. arabica* (Staver et al. 2001), whereas *C. canephora* varieties remain more resistant (see table 3 in Marsh 2007). Coffee leaf rust (*Hemileia vastatrix*) is the main disease of *C. arabica* in Latin America (Avelino et al. 2007); the latest (2012–2013) outbreak lowered harvests by 10%–70% in several Latin American countries, including Peru (JNC 2014), Mexico (GAIN 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 PD 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; 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, López-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). In addition, 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). Therefore, coffee disease cannot be reduced by shade management alone, but it can in combination with modified humidity, predator management, and local and regional landscape management.

(3) Shade, yield, and quality. The interactions among shade, yield, and the resultant coffee quality (or *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 intensified practices, and financed programs that often included free or subsidized agrochemicals (Rice PD and McLean 1999). Although 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 in which yield in low- and high-shade treatments have been categorically compared have shown lower yields with shade, higher yields with shade, and no difference; however, studies in which a continuous gradient of shade was examined have predominantly revealed that intermediate shade levels (approximately 35%–50%) produce the highest coffee yield, which is probably because of the balance maintained between optimal temperatures in shaded environments and optimal photosynthetic rates in unshaded environments (Soto-Pinto et al. 2000 and the references therein). Although it is difficult to compare findings across studies because of geographical differences, it is clear that yield is not solely or linearly linked to shade tree density or diversity.

Recent work has also shown that cup quality is the result of a variety of interacting factors that include environmental conditions, field management, adequate processing and drying, and roasting. Surprisingly, breeding efforts for coffee have largely ignored quality and have been 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 (lower than 500 m) and effects on cup quality that can be either positive or negative 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.

(4) Livelihood, cooperatives, and shade coffee management. Farm size, cultural history, and a farmer's relationship with cooperatives can influence farmer management decisions and use of shade vegetation (Moguel and Toledo 1999). In Veracruz, Mexico, small-scale producers (1–5 ha) used lower levels of agrochemicals per farm than did larger-scale farmers (with more than 45 ha), which resulted in fewer soil and water contamination problems. However, many of these small-scale farmers are slowly adopting several of the intensified management practices used 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 than did larger (over 100 ha) collectively managed holdings (Méndez et al. 2007, 2010a); furthermore, tree diversification levels were highest for cooperatives that clearly defined who would 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 wider variety of tree products and on-farm benefits (Méndez et al. 2010a). These farmers managed their coffee plantations both for household consumption products and for income from coffee. In contrast, collectively managed farms are focused almost entirely on producing coffee for income, partly because of the challenge of distributing both the work and the benefits to obtain more on-farm products. The only noncoffee product on which collective farm members are dependent and actively collect is firewood; collective cooperatives have an open policy for their members to aquire firewood for household use (Méndez et al. 2007, 2009). Therefore, well-organized cooperatives, if they are 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), which potentially creates 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 associations and access to land, water, loans, houses, and equipment (e.g., Bacon et al. 2008). Research shows that individuals working at the production end of the coffee value chain (i.e., the farmers and countries) continue to receive a very small fraction of the profits (Gresser and Tickell 2002). Coffee pickers and laborers (who are often migratory) are the most marginalized actors within the coffee value chain (Gresser and Tickell 2002), because they are vulnerable to shifts in production, climate, and market demands (CEPAL 2002, Bacon et al. 2008) and are paid by the pound or volume of coffee cherries harvested, making as little as $2 per day in many parts of the world (Gresser and Tickell 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 (Gresser and Tickell 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 (Gresser and Tickell 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, although 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 other vulnerabilities persist (Bacon et al. 2008, Méndez et al. 2010b).

(5) Shifting economic incentives linked to global coffee markets and value chains. One avenue to address declines in coffee profits and sustainable management is 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 billion to $32 billion (SCAA 2012). This market has expanded rapidly in the past 20 years, with estimates of total retail specialty coffee sales—excluding Walmart—continuing to increase in the past decade (figure 3). The specialty coffee market supports a distinct value chain. By definition, specialty coffees distinguish themselves from bulk coffee on the basis of a variety of factors that include quality (Läderach et al. 2006), sustainability, and closer relationships with growers (Bacon et al. 2008). Within the specialty coffee market, there are several types of certification for *sustainability*; the *fair trade* label is focused on the trade relationships, and *organic* requires soil conservation and prohibition of agrochemicals and genetically modified crops, among other criteria (Méndez et al. 2010b). Smithsonian's *Bird Friendly* certification program has the highest agroenvironmental standards, requiring *organic* certification and more than 10 species of shade trees, as well as guidelines to conserve soil and water. *Rainforest Alliance certified*, *UTZ certified*, and *fair trade* also have several agroenvironmental 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 such eco-label. It is estimated that more than 10% of the coffees sold in 2007 carried at least one sustainability certification, and it is expected that this percentage will continue to increase rapidly (Giovannucci et al. 2008). In addition to the certifications previously mentioned, firms, nonprofit 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) Association and two

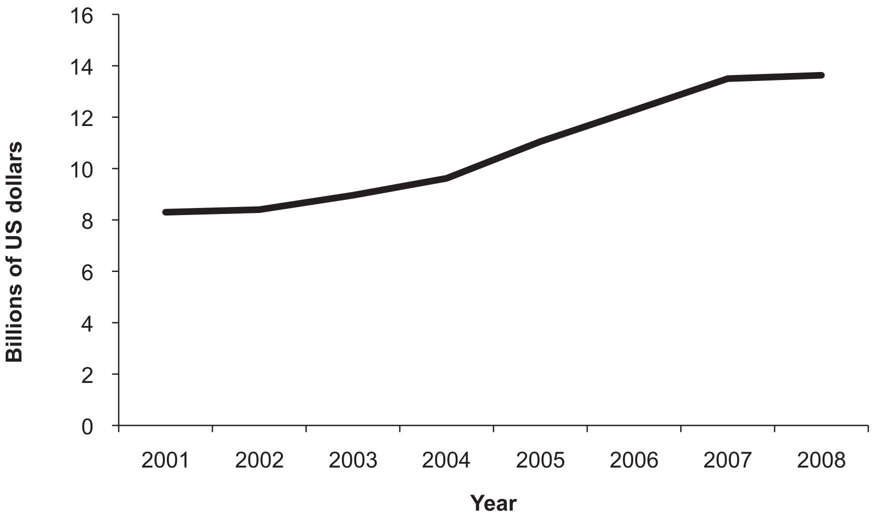

Figure 3. Size of the specialty coffee market in billions of US dollars. Source: Specialty Coffee Association of America (2012).

initiatives started by large coffee companies that do roasting and retailing, Starbucks's Coffee and Farmer Equity Practices and Nestlé'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 (Giovannucci 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 who participate in cooperatives connected to *fair trade* certification often have more access to credit and technical support (Méndez et al. 2010b) and often receive higher prices for their coffee, buffering their 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* certification 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 because 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 through the certification processes.

Biodiversity and ecosystem services

Shaded coffee plantations are increasingly valued for their contributions to biodiversity conservation and the provisioning of ecosystem services (Tscharntke et al. 2011, De Beenhouwer et al. 2013). Since the 1990s, shade coffee has been noted for its contributions to conserving plant, arthropod, bird, bat, and nonvolant mammal diversity (Perfecto et al. 1996, Donald 2004). More recent studies have documented patterns of bird, ant, and tree biodiversity declines, 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 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). Therefore, as a whole, ecosystem services tend to decline as forests are converted to shade coffee and as shade coffee is converted to low-shade coffee systems (De Beenhouwer et al. 2013). According to our review, unique ecosystems across varying coffee vegetation management styles have been directly measured in more than 70 studies, including pollination (7 studies), pest control (42 studies), climate regulation (13 studies), and nutrient cycling (10 studies). Although distinct methodologies and methods of measuring response variables (e.g., predator species richness versus abundance) complicate meta-analyses for each unique ecosystem service, we found positive effects of shade on ecosystem services in approximately 58% of the pollination studies, 60% of the pest control studies, 100% of the climate regulation studies, and 93% of the nutrient cycling studies (table 1; the literature search details are available in supplemental appendix S1).

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.), they 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 ha in aboveground biomass compared with unshaded coffee monocultures (Palm et al. 2005). In Mexico, Soto-Pinto and colleagues (2010) found that *Inga*-shaded *organic* coffee maintained carbon aboveground (56.9 tons of carbon per ha) and in the soil (166 tons of carbon per ha) to an extent equal to that of nearby forests, and traditional polyculture coffee maintained more carbon than all other examined land-use types. If we consider that scant-shade systems sequester an additional 53 tons of carbon per ha more than unshaded systems do (Palm et al. 2005), the conversion of even 10% of unshaded 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 on shaded farms. Ants and spiders, for example, reduce the damage caused by the coffee berry borer, *Hypothenemus hampei* Ferrari (Perfecto and Vandermeer 2006), and the coffee leaf miner, *Leucoptera*

Table 1. Impact of increasing the vegetation complexity of shade coffee on pollination, pest control, climate regulation, and nutrient and sequestration ecosystem services.

Effect	Pollination	Pest control	Climate regulation	Nutrients and sequestration
Positive	More pollinator species[1], more abundant pollinators[2], native bees[3], and social bees[3]	More parasitoids[8], more abundant[9] and more species[10] of predators, more available predator nests[11], removal of pests[12], less abundant[13] and less damage from[14] pests	More frequently wet leaves[24]; lower air, soil, or leaf temperatures (mean maximum or mean)[25]; less global, photosynthetically active, or net solar radiation[26]; fewer and smaller landslides[27]; lower wind speeds[28]; lower soil evaporation rates and plant evaporative transpiration[29]; relatively more extractable water in soil[30]; more soil moisture[30]; higher precipitation capture[31]; less humidity and fewer solar radiation fluctuations[32]; less frost damage[33]; fewer intraday fluctuations in temperature[34]; lower rate of cooling of night air[34]	More above ground carbon storage[35], more total soil organic carbon[36], more nitrogen mineralization[37], less nutrient pollution[37], more active soil microbes[38]; higher soil pH and cation-exchange capacity, more calcium and magnesium, less phosphorus[39]; higher concentrations of nitrogen in leaves[40]; higher proportions of phosphous available to agricultural crops[41]
Neutral	No impact on pollinator abundance[4] or pollinator diversity[5]	No impact on pest[15], predator[16], or prey[17] abundance or on predator species richness[18]; no removal of pests[19]		No impact on soil organic carbon[42]
Negative	Less abundant[6] and fewer[7] pollinator species	Higher pest abundance[20] and species richness[21], less abundant[22] and fewer[23] predator species		

Note: The numbered notes in the table correspond to the references in supplemental appendix S1, which also contains a description of the literature search method.

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%, which amounts to values that exceeded $44–$105 per ha per year (Kellermann et al. 2008) and $75–$310 per ha per year for farmers (Karp et al. 2013). Pollinators are also crucial 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 the 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 per ha (Karp et al. 2013) and pollination services at $56 per ha (Ricketts et al. 2004), the additional pest control and pollination contributions provided could exceed $2.3 billion and $1.7 billion, respectively. Overall, these studies highlight the great potential for increased carbon sequestration, pest control, and pollination services within shade coffee systems.

Connectivity and resilience to climate change

Shade coffee systems also help 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 crucial during the coffee bloom and are able to maintain reproduction and gene flow processes for plants 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; in many countries, including El Salvador, Guatemala, and Costa Rica, more than 30% of the area surrounding coffee regions (50-kilometer radius) falls within protected areas (Jha et al. 2012). Because organisms such as 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 that result from 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 for coffee farmers, but farms with more-complex vegetation (i.e., greater tree density and tree species richness) experience significantly fewer posthurricane landslides (Philpott et al. 2008b). Coffee farmers, realizing the enhanced risk in less-shaded fields, have engaged in posthurricane mitigation focused on increasing the planting of more shade trees within their coffee fields (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 (table 1; Lin et al. 2008). Coffee depends on seasonal rainfall (or irrigation) for flowering and leaf photosynthesis; therefore, coffee growth rates and yields are highest in specific precipitation and temperature ranges (Lin et al. 2008 and the references therein). We spatially quantified the change in coffee suitability in Mesoamerica using the same methodology as that described in Läderach and colleagues (2011) for Nicaragua and in Schroth and colleagues (2009) for Chiapas, in Mexico. We used WorldClim (*www.worldclim.org*) as the current climate database, the most representative Global Climate Models of the Fourth Assessment Report for the Special Report on Emission Scenarios A2a (business as usual) emission scenario, and existing data on 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 on the basis of presence data and the climate at these locations. The established relationship between the current climate and the suitability index are then projected into the future. The model is based on the assumption that, in the future, the same climatic factors will drive coffee growth as do 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 (figure 4). *Coffee suitability* in this context refers to areas that are climatically suitable to grow coffee, such that 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 upslope by 300–400 m in order to compensate for the increase in temperature (Läderach et al. 2013). The shift in elevation will increase the pressure on forests and the environmental benefits they provide to downstream communities.

Synthesis

When synthesizing research on global coffee distribution and cultivation practices, livelihoods, biodiversity, ecosystem services, and climate resilience, it becomes 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 constitute less than 24% of the coffee production areas surveyed in 2010, and the coffee expansion in the past two decades has been typified by intensive unshaded practices. Millions of coffee farmers continue to struggle for survival, despite the production of high-quality coffees and the generation of crucial ecosystem services (Bacon et al. 2008). Although some ecosystem services are well known to coffee farmers (Cerdán et al. 2012), many others remain obscure to external agencies because of the indirect nature of their services and the potential for interaction (Bennett et al. 2009). Henry and colleagues (2009) examined interactions between plant biodiversity, regulating (carbon sequestration), and provisioning (food production) ecosystem services in Kenya and found that increasing carbon sequestration by adding more trees could have a negative effect on food production. In another example, Méndez and colleagues (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 independently 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.

(1) Improve certification and ecosystem service valuation. Although certification is a common default approach used to integrate sustainable agriculture with worker livelihoods, the certification approach is challenged by the limited nature of the certifications available and the organizational and financial costs of certification. The existing certifications have unique ecological standards, offer distinct economic incentives to different agents (directly to growers, to exporters, or to certification agencies), and also differ in the price premium provided (Calo and Wise 2005, Raynolds et al. 2007, Bacon et al. 2008). 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, although *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 in 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'

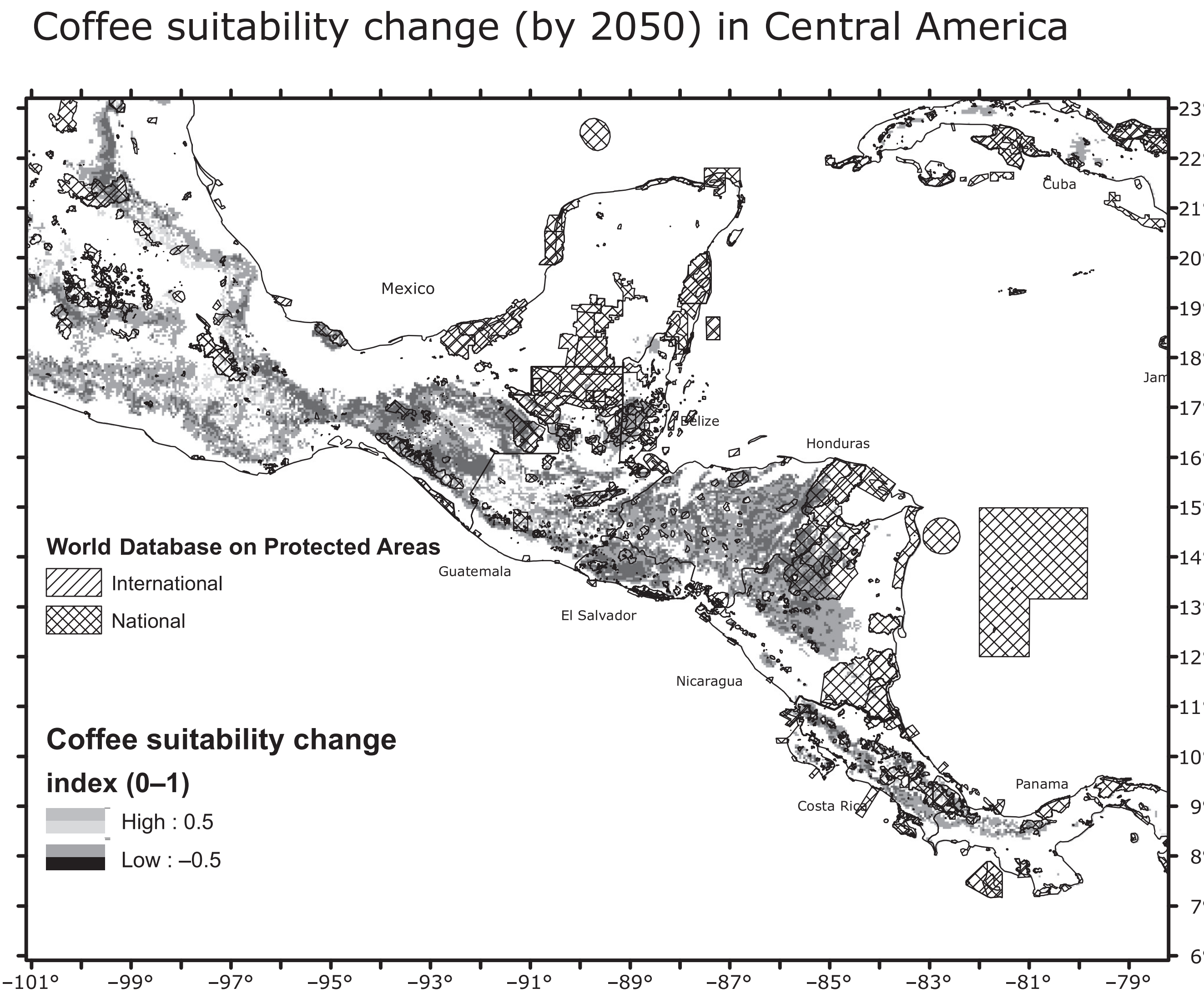

Figure 4. Distribution of coffee suitability in 2050 and the current protected areas in Mesoamerica. Sources: The data are from the World Database on Protected Areas (**www.wpda.org*****) and the International Center for Tropical Agriculture's Decision and Policy Analysis tool (*****http://dapa.ciat.cgiar.org*****).***

profit are earned. In this way, 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. In future work, the support needed from financial, institutional, and community agencies in order to successfully transition noncertified farmers to *organic*, *fair trade*, or *biodiversity-* or *livelihood-friendly* coffees should be explicitly investigated.

(2) Diversify coffee farms. For both economic and ecological resilience, the diversification of crops and livelihoods is essential for coffee producers (Rice RA 2008). In this review, we describe how a diverse array of crops and shade trees provides farmers with alternative income sources in cases of crop losses and price fluctuations; income across the growing season; food for home consumption; and improved fertilization, erosion control, and habitat for pollinators and predators. Therefore, 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 the 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).

(3) Change local and global policy. Since 1989, the role of national governments directly influencing global coffee markets and prices paid to producers (through the International Coffee Agreement) 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 populaces and in protecting ecosystem services. Payments for ecosystem services provide one avenue for compensation 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 payments for ecosystem services or integrating them with the practices of potential stakeholders or government agencies create real challenges (van Noordwijk and Leimona 2010). Therefore, 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 be good stewards of the land while making a living.

Conclusions

Our findings show that, although global coffee acreage has decreased since 1990, cultivation has grown dramatically in Asia and has been accompanied by declining levels of diverse-shade coffee, which threatens 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 that 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 the 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 have documented that, in many of the landscapes that generate important ecosystem services, the benefits are not necessarily harvested in terms of income, incentives, and opportunities. In order for coffee landscapes to be sustainable for humans and their ecosystems, we need to (a) better incorporate human well-being and livelihoods into global concepts of sustainability, (b) encourage the diversification of coffee farms to promote greater resilience to changes in global markets and climates, and (c) improve the valuation and reward for ecosystem services through certification and other systems in order to compensate farmers for the innumerable benefits that shaded landscapes provide. Building synergistic and cooperative relationships among 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.

Acknowledgments

We express our gratitude to the coffee farmers of Mexico, Nicaragua, El Salvador, Guatemala, Peru, Indonesia, and Costa Rica for their support and permission to conduct research with their families, in their communities, and on their land.

Supplemental material

The supplemental material is available online at *http://bioscience.oxfordjournals.org/lookup/suppl/doi:10.1093/biosci/biu038/-/DC1*.

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