Synergies between Agricultural Intensification and Climate Change Could Create Surprising Vulnerabilities for Crops

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An inevitable consequence of global climate change is that altered patterns of temperature and precipitation threaten agriculture in many tropical regions, requiring strategies of human adaptation. Moreover, the process of management intensification in agriculture has increased and may exacerbate vulnerability to climate extremes. Although many solutions have been presented, the role of simple agroecological and agroforestry management has been largely ignored. Some recent literature has shown how sustainable management may improve agroecological resistance to extreme climate events. We comment specifically on a prevalent form of agriculture throughout Latin America, the coffee agroforestry system. Results from the coffee literature have shown that shade management in coffee systems may mitigate the effects of extreme temperature and precipitation, thereby reducing the ecological and economic vulnerability of many rural farmers. We conclude that more traditional forms of agriculture can offer greater potential for adapting to changing conditions than do current intensive systems.

Keywords: agricultural intensification, agroecological resistance, climate change adaptation, climate extremes, ecological management

Global climate change is currently affecting many ecological systems and may have large impacts on agricultural systems. Although increased management intensification has been promoted in agricultural systems to control for variability, certain intensive management regimes may be more vulnerable to the effects of extreme climate.

Climate uncertainty and agricultural vulnerability

Current climate science provides substantial evidence that climate extremes are becoming more exaggerated. Along with the well-publicized rise in average global temperature, there is mounting evidence of more frequent extreme climate events, such as category 4 and 5 hurricanes (Hoyos et al. 2006), as well as El Niño Southern Oscillation (ENSO) events (Dunbar et al. 1994). Such changes in global climate patterns portend potentially large effects on both human and natural systems, resulting in greater vulnerability for many people in the world, as was vividly demonstrated by Hurricane Katrina in 2005.

Agriculture is especially vulnerable to climate events. Many crops are sensitive to changes in temperature and precipitation, and these crops frequently have a narrow threshold for success (Oram 1989, Mendoza and Villanueva 1997, Gregory and Ingram 2000). Therefore, temperature and precipitation changes associated with extreme events will affect crop production. Such sensitivities may be crucial in the tropics, where most agriculture is in rain-fed systems and climate change has a potentially large influence on productivity (Slingo et al. 2005). Increasingly, research has focused on the importance of crop sensitivity to drought and to periods of heat stress at particular stages of development (Challinor et al. 2005, Porter and Semenov 2005). Temperature is an important climate threshold for food crops because high temperatures that coincide with critical phases of the crop cycle can dramatically lower yield. In some crops that are well characterized, the reproductive limits have been narrow. Maize exhibits reduced pollen viability at temperatures above 36 degrees Celsius (°C), and pollen sterility in rice is brought on by temperatures in the mid-30s (Porter and Semenov 2005).

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However, it is not just the long-term, slow-changing climate effects, such as gradually rising temperature or gradually changing rates of precipitation, that threaten crop production. Extreme climate events that occur rapidly over a short time span are perhaps more threatening to agriculture. Maximum temperatures on a single day and maximum one-day precipitation totals are examples of extreme events that are often related to crop damage. If these extreme events coincide with an important step of the crop developmental cycle, production can be dramatically reduced. For example, eight-hour heat pulses that were applied to wheat during anthesis to mimic elevated daytime temperatures resulted in a decrease in harvest due to damaged flower development (Wollenweber et al. 2003). This result demonstrated how a higher maximum temperature on a single day of flowering could affect production.

That agriculture is threatened by expected climate change is now beyond debate, and most climate scientists are not optimistic about the potential to reverse course (IPCC 2007). Indeed, even if carbon dioxide production were to cease completely today, the climate would continue to change for many years to come. Consequently, the need for adaptation to climate change has entered the discourse and should be considered a major coping mechanism, perhaps at least as important as remediation and restoration (Berry et al. 2006, IPCC 2007). The Intergovernmental Panel for Climate Change synthesis report (IPCC 2007) states that climate change will have a major impact on food and water resources and suggests that adaptive measures must be developed. Accepting this necessity and focusing on agriculture, we must ask, What would adaptation look like?

The question of agricultural management and intensification

While there is growing concern about the impacts of climate change on agriculture, another ongoing process in agriculture has been the intensification of food production. The "green revolution," a driving force in the intensification of agriculture throughout the past half-century, sought to increase food production for the starving masses, and indeed the increased use of green-revolution technologies has increased yield and doubled global cereal production in the past 40 years (Tilman et al. 2002). However, the movement toward increased production transformed agriculture from small-scale, traditional agroecosystems, where most of the inputs for production came from within the biological components of the agroecosystem, to modern intensive systems, where agrochemicals were substituted for functional ecological processes (e.g., ecosystem services to agriculture; Zhang et al. 2007). This transformation allowed the development of large-scale monocultures with little resemblance to the natural systems around them (Gliessman 1998).

These systems were initially developed as a way to provide greater control over the ecological processes affecting agriculture and thus to escape the vagaries of natural stochasticity, but, ironically, this ongoing process of intensification may make agroecosystems more vulnerable to changing climate as they become further removed from natural systems. Although this move toward intensification has been motivated by a legitimate need for greater production, it may also carry with it many unintended environmental consequences, including increased nutrients and toxins in water sources, pesticide poisoning, and bioaccumulation (Tilman et al. 2002), as well as greater vulnerability to climate change.

The pattern of agricultural intensification is usually associated with a change in particular ecosystem and plant characteristics, and it varies dramatically among agroecosystems. Nevertheless, certain trends are clear. There is a change from locally adapted genetic varieties in traditional systems to high-yielding, input-intensive varieties in the modern system, in which the nutrient and water requirements of the new variety are often higher than what is available under natural conditions. The increased demand for nutrients and water is exacerbated by the fact that the process of intensification also alters the resource cycling of the system. Traditional agroecosystems are generally closed systems—nutrients and water are cycled within the system for efficient usage. However, modern intensive agriculture generally exhibits an open system, in which nutrients and water are often lost from the system and external inputs must be implemented to augment poor resource levels (Pearson 2007). Furthermore, the modern system relies on outside infrastructure (e.g., a petrochemical industry supporting the pesticide or fertilizer industry) to help acquire and maintain the necessary resources for crop production. Lastly, the more intensive system has moved from a state of high diversity (in terms of crop species and genetic varieties) throughout space and time, with different crops potentially harvested throughout the year at different levels of the canopy from the same plot, to a state in which a single crop is grown annually over large spatial extents and in which farmers depend on one crop to support their livelihood (Altieri 1995, Matson et al. 1997, Gliessman 1998).

Most important, this trend toward agricultural intensification is invariably accompanied by an increasing need for external resources, including both water and nutrients, in agricultural systems throughout the world. The Food and Agriculture Organization of the United Nations (FAO 2001) reports that land under agricultural irrigation increased by 72% worldwide between 1961 and 1997, with Central America and the Caribbean experiencing an 80% increase (FAO 2001). This has been accompanied by an increased use of pesticides and fertilizers, with Central America and the Caribbean applying an additional 100 million metric tons during the same period (FAO 2001). Many adopters of such technologies have reached maximum yield potential, meaning that further increases in water and fertilizer use will not lead to greater production (Tilman et al. 2002). The move toward greater irrigation has become increasingly difficult as water sources have been reduced as a result of overexploitation and salinization (Rosenzweig et al. 2004). Furthermore, the excessive use of pesticides has been a worldwide concern since the publication of Rachel Carson's *Silent Spring* in 1962.

Although the move toward agricultural intensification was intended to lead to greater production in crops, it has resulted in less diverse, less physiologically efficient (because of the need for external inputs), and less adaptable systems. Essentially, the ability to manage and provide the resources for these systems has resulted in a community of plants (crops) with reduced ability to respond to the selection pressures of natural conditions (Chapin 1980). Thus, under potential regimes of climate change, these intensified systems may experience lower productivity, higher vulnerability, and reduced sustainability.

There is already well-documented, ongoing change in the mean and variability of climates, leading to rising temperatures and more extreme weather events (IPCC 2007). This increasing variability in climate can lead to greater vulnerability for agriculture, as argued above. The historical pattern of agricultural intensification may increase that vulnerability, because more intensive, low-diversity systems are not generally buffered against any significant environmental change, let alone the sorts of large-scale changes we now expect. Ultimately, the question is, Does the pattern of agricultural intensification exacerbate an already ongoing trend of increased vulnerability in agricultural production due to climate change?

Management intensity and agroecological resistance

The search for potential agricultural adaptations to climate change has been broad in scope, but generally the proposed adaptations have required still more technical management and human intervention. In agriculture, researchers have focused on the genetic modification of crops (Orindi and Ochieng 2005, IPCC 2007), on changes in the location of production (Assad et al. 2004), and on the development of models for climate forecasting (Hansen 2005). Less commonly recognized is that management practices could contribute significantly to the arsenal of options available in the pursuit of rational adaptation to climate change. Some evidence is beginning to emerge regarding the extent to which agroecological practices can offer resistance to the impacts of extreme climate events (Holt-Giménez 2002). Further, the agroecological resistance evident in some agricultural systems appears to be a result of obvious microhabitat modifications (Kiepe and Rao 1994).

Holt-Giménez (2002) studied the role of agricultural management intensity in relation to Hurricane Mitch, an extreme climate event that hit Nicaragua and Honduras in October 1998, causing great disturbance to much of the agricultural land in this region. Holt-Giménez (2002) examined the agroecological resistance—defined as the ability of a farming system to resist the impact of disturbance (Pimm 1984, Herrick 2000)—of farms under agroecological versus conventional management in order to determine whether differences in management lead to differences in hurricane impacts. The agroecological farms used sustainable land management practices, including structural, agronomic, and agroforestry techniques. Conventional farms lacked those practices and used a mix of traditional and "semi-technified" practices (table 1). The results showed that agroecological farms had, in general, more topsoil and higher field moisture measures, more vegetation within the system, and lower economic losses than the conventional farms (Holt-Giménez 2002). These results suggest that agroecological practices rendered a higher resistance to this climate event, which translated into lower vulnerability and higher long-term farm sustainability.

Another example of agroecological resistance in relation to management intensity comes from Tengo and Belfrage (2004), who compared land management practices in Sweden and Tanzania to examine how the various practices responded to change and uncertainty in the agricultural environment (table 1). While farmers in Tanzania were more concerned with heat tolerance and those in Sweden were concerned with cold tolerance, both areas suffered from seasonal drought—including irregular ENSO events—that affected production in Tanzania. The disturbance regimes in the two case studies differed in magnitude, intensity, and predictability, but similar successful management practices were found at both sites. In both locations, the more traditional practices, which were generally more ecologically complex, proved to be more sustainable in the face of climate extremes. Practices that incorporated wild varieties (adapted to temporary drought) had an enhanced capacity to respond to changing local environmental conditions. Temporal and spatial diversity of crops, and practices such as polyculture or intercropping, were also shown to regulate pest outbreaks and to promote water conservation, which limited the effect of seasonal drought. The researchers concluded that complex agroecosystems would be more sustainable in the future and would provide more security for agricultural production.

These two examples suggest that modern, intensive agricultural systems may have lower resistance and higher vulnerability to extreme climate events, potentially affecting the long-term sustainability of crop production under global climate change (Gliessman 1998). Therefore, it is important to further explore the relationship between farming intensity and agroecological resistance, to understand how management intensity may contribute to or mitigate agricultural vulnerability. Here we present further evidence of this phenomenon, demonstrating the underlying mechanisms of agroecological resistance to climate change by using one specific system that is especially important in tropical regions: the coffee agroforestry system. Coffee agriculture provides a highly relevant example of how management intensification may be increasing the vulnerability of farmers, and of how preserving ecological stability may yield unexpected outcomes of greater resistance to climate extremes.

Climate change and the coffee agroecosystem

Coffee agroecosystems provide the agricultural basis for many rural farmers throughout the developing world, and changes in coffee commodity chains and in management

Table 1. Successful agroecological management practices and their functions in agricultural systems described by Holt-Giménez and Tengo and Belfrage.

Agroecological management practice	Function
Described in Holt-Giménez (2002)	
Contour plowing, rock and vegetative contour bunds, contour ditches, terraces	Soil and water conservation and management
Cover cropping/intercropping/relay cropping with grains and legumes; intensive, in-row tillage and reduced use of chemical inputs; compost, vermiculture, animal manure; integrated pest management (traps, organic pesticides and repellants, beneficial insects)	Fertility, soil building, weed and pest control, water conservation, soil protection, increased land equivalency ratio
Woodlots, multistory and alley cropping, vegetative strips, live fences	Fuel, fodder, timber, fruit, reduction of runoff, nutrient pumping and cycling, habitat for beneficial insects, shade
Described in Tengo and Belfrage (2004)[a]	
Mixed grains, cereals intercropped with leguminous plants, crop rotation	Polyculture, local-variety improvement, plant production
Hoeing (manual weeding), crop rotation and intercropping within fields, undersown crops and catch crops to deter weeds	Weed-control management
Protection of pest-controlling species, improved habitat for pest-controlling species, manual removal of pest insects on crops, intercropping and crop rotation within fields, crop diversification, rotational grazing, alternating grazing of different livestock species	Pest-control management
Integrated production of crops and livestock; composting of manure, dung, and other organic material; incorporation of residues and weeds in soil; use of nitrogen-fixing crops; timing of manure application	Nutrient supply and recirculation
Enhancement of species' habitats, social taboos on destroying pollinator species, use of beehives	Pollination protection and enhancement of pollinators
Indicators for timing of planting and harvest, weather prediction, and field condition	Information services and biological indicators

a. These methods were practiced in both Tanzania and Sweden.

pressures have increased the economic vulnerability of many farmers (Bacon 2005). Although the coffee crop represents a luxury product rather than a basic food product, and threats to coffee agriculture may not threaten food security per se, many farmers depend on the crop for their livelihoods. Furthermore, the simultaneous trends of climate change and management intensification occurring in coffee agroecosystems exemplify the current vulnerabilities experienced in all agricultural systems.

The process of coffee intensification

Traditionally, coffee has been grown under the diverse canopy of shade trees in what is known as an agroforestry system. This diversity of trees—including many native canopy trees, but also fruit, nut, and lumber trees that farmers extract for household purposes—has traditionally reduced the economic and social vulnerability of farmers (Bacon 2005). However, in pursuit of increased production—and motivated by government incentives—coffee farmers have gradually removed shade trees within coffee agriculture. Active deforestation is based on the assumption that shade trees compete for sunlight, nutrients, and water with the coffee plants, and that this increased competition may lower coffee yields. Although the evidence for increased production with lower levels of shade is erratic (see, e.g., Soto Pinto et al. 2000), some of the coffee literature has supported this conclusion (Fournier 1988), and to be sure, there is some empirical support for such an assumption. A crop plant with unlimited resources will certainly produce more than a crop plant with a restricted supply (Castillo and Lopez 1966, Fournier 1988).

These studies, along with a general assumption that more light would lower fungal disease outbreaks, spurred coffee intensification programs in the 1990s throughout Central and South America. These programs provided incentives to farmers to move toward more intensive methods of production with less diversity and a lower density of shade trees (Nestel 1995). Furthermore, recent changes in the world market have caused coffee prices to decrease dramatically. This has exacerbated the deforestation of coffee agroforestry systems (Giovannucci and Koekoek 2003), leading to a system in which less shade is preserved and coffee is grown with a large regimen of pesticides and herbicides.

Consequently, coffee agriculture has been moving progressively toward an intensive management regime. There is now a large range of management systems, from traditional rustic agroforestry, in which the coffee plants simply replace the natural forest understory with no modification of the original forest canopy, to the very intensive modern sun monocultures. There are many gradients of shade in between these two extremes, providing variable amounts of shade to the crop and requiring various amounts of external infrastructure for crop maintenance (figure 1; Moguel and Toledo 1999). Thus, within the coffee system, the amount of shade cover over the crop is a proxy for the management intensity of the agroecosystem (Beer et al. 1998).

Although climate fluctuations are already occurring, very little research has been conducted to better understand the sensitivity of coffee agroecosystems to changes in temperature and precipitation. Moreover, there has been little movement to develop adaptive agricultural methods to protect coffee agroecosystems from climate change (Adams et al. 2003). Because coffee has been traditionally grown as a rain-fed crop throughout much of Latin America, and very little access to irrigation is available in many coffee-growing regions, it is important to learn how coffee management can maximize water use from precipitation. The trend toward less shaded coffee systems, in combination with increasing climate variability, may become critical to coffee production as precipitation rates decline.

Coffee requirements and farmer vulnerabilities to climate

Although the specific water requirements of coffee in different agricultural settings have not been quantified, it is well known that coffee production is dependent on the seasonal precipitation cycle of the tropics (Carr 2001). Water availability from precipitation may affect several key functions for the crop plant. First, an extended period of drought is required for the flower buds to form (Magalhaes and Angelocci 1976). The flower buds then open simultaneously in response to sporadic dry-season rain and remain receptive to pollination for 48 hours after bud opening (Cannell 1983). The beginning of the rainy season signals a period of rapid leaf flush and fruit growth, which continues throughout the season (Montoya and Sylvain 1962, Huxley and Ismail 1969, Cannell 1983). Water availability has also been found to affect the maintenance of maximum photosynthetic rates (Nunes et al. 1968), high fruit set levels (Mayne 1934–1938), and fruit size (Wormer 1964, Cannell 1985).

Coffee phenology is therefore vulnerable to both the quantity of precipitation and the timing of precipitation events. Coffee plants are susceptible to plant stress and damage during the dry season and especially during times of drought, which can occur at important points of flowering and fruit development. With higher climate variability, crops may be subjected to more erratic precipitation events, leading to increased water stress within the system. In addition, extreme events such as ENSO can cause an extended drought during the dry season at important developmental cycles and put high stress on the plants, thus reducing crop production dramatically (Salinas-Zavala et al. 2002).

Coffee plants are also quite sensitive to changes in microclimate. The optimal temperature range for Arabica coffee is between 18°C and 21°C (Alegre 1959), and shade helps keep the coffee cooler during the day and warmer at night (Kirkpatrick 1936). Experiments have shown that at temperatures above 24°C, the net photosynthesis of coffee decreases markedly, approaching zero at 34°C (Nunes et al. 1968, Cannell 1976). Above 23°C, fruit development and ripening are accelerated, leading to loss of quality; below 18°C, growth is depressed (Camargo 1985). Furthermore, moderately shaded Arabica coffee plants have photosynthetic rates three times higher than coffee leaves under full sun (Nutman 1937). DaMatta (2004) concluded in his study of ecophysiological constraints of coffee that the benefits of shade increase as the environment becomes less favorable for coffee cultivation.

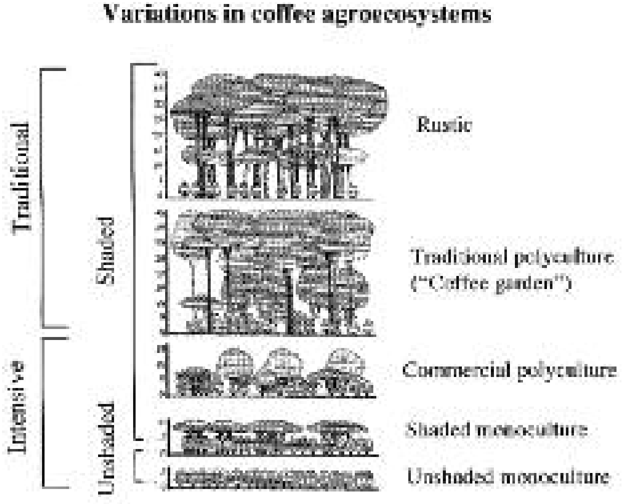

Figure 1. Variations in coffee agroecosystem management intensity, ranging from traditional rustic systems to intensive, unshaded monocultures. Adapted from Moguel and Toledo (1999).

It is important to consider these vulnerabilities, because they have the potential to do considerable harm to the many farmers who depend on coffee for their livelihoods. For example, previous ENSO years have shown a decrease of 40% to 80% in coffee crop production within southern Mexico, leaving many small producers impoverished and without other means to earn income (Castro Soto 1998). In Mexico, approximately 3.5 million people depend on coffee production (Calo and Wise 2005). Therefore, large-scale climate events that hit coffee-growing regions can affect many small producers and threaten the livelihoods of many people.

The role of agroforestry in reducing vulnerability

Previous studies have investigated the benefits associated with shade cover in coffee agricultural systems and with traditional types of management such as agroforestry systems. These benefits include biological conservation, integrated pest management, and pollination services (Beer et al. 1998, Klein et al. 2003). Vital investigations, in light of current climate concerns, have shown that shade trees create a better microclimate for crop plants by mitigating temperature and humidity fluctuations, thereby maintaining a cooler and moister atmosphere than open systems (Beer et al. 1998). Shaded systems can reduce leaves' maximum temperatures and humidity variations within the system (Kirkpatrick 1935, Barradas and Fanjul 1986). Lin (2007) has also shown that increased shade cover reduced temperature at the most important point of the day, when plants were most heat stressed. A low-shade site experienced higher temperatures and lower relative humidity than the high-shade site, indicating that the advantage provided by the shade is precisely what a manager should be looking for in a mitigation strategy (figure 2). The presence of shade also maintained higher temperatures in the evening, when plants were most cold stressed (figure 2; Lin 2007).

Such microclimate controls for plants may provide substantial abiotic contributions to sustainability. First, the ability to maintain temperature levels closer to the maximum production temperature will allow for better management of plant physiological processes and provide farmers with the tools to optimize plant photosynthetic rate. Second, lower temperatures and higher humidity may contribute to better water management, minimizing loss through evapotranspiration. In addition, by shielding plants from solar radiation, the shade cover will protect crops from stomatal closure when water resources are low.

Shade trees also provide protection from other climate features, such as wind and storm events, which can defoliate coffee trees and decrease yield levels through premature fruit drop (Stigter et al. 2002). By reducing the speed of winds passing over the crop strata (Schroeder 1951), shade trees may potentially lead to less water loss through transpiration and soil evaporation (Teare et al. 1973). Lin (2007) showed that systems with greater shade had greater water availability because of decreased evapotranspiration from the coffee and soil layer, and Wallace (1997) found that the shade canopy of an agroforestry system may lead to higher water conservation by decreasing water runoff, nutrient and fertilizer drainage, and soil erosion.

The effect of shade on competition and coffee yield

Although the reduction of shade tree cover purportedly benefits small farmers through increased production, the relationship between shade cover and yield is still inconclusive (Beer et al. 1998). While some studies show a decrease in yield with more shade (Lagemann and Heuveldop 1983, Nolasco 1985), others show an increase (ICAFE 1989, Ramirez 1993), and still others have observed a maximum yield at intermediate levels of shade (Muschler 1997, Soto-Pinto et al. 2000). The results have been difficult to interpret because of the large variation in the factors that affect production (e.g., altitude, precipitation, variety, soil type, management) and the differences among these factors within the various studies (Beer et al. 1998). Therefore, the move toward highly intensified systems seems premature, considering the increased risk of vulnerability to climate extremes.

Within coffee agriculture, one reason that shade has been maintained is because it prevents overbearing of fruit on a branch, therefore preventing biennial fluctuations in yield (Cannell 1983). When more fruit is produced than the system can support, new roots and shoots die back to provide the nutrients necessary for the fruit. However, this adaptive measure leads to plant damage that lowers the following year's production levels (Cannell 1983).

In general, the consensus within the literature is that the positive aspects of shade cover increase as the general environment for crop growth becomes less suitable for coffee (Muschler 1997, DaMatta 2004)—as, for example, when climate extremes increase. However, more studies are required to understand the precise position of this trade-off point (Nair 1997, Beer et al. 1998, Somarriba et al. 2001) in order to determine proper recommendations for shade management. Such research will also be beneficial for other important export crop plants, such as tea and cocoa, which are also traditionally grown in agroforestry systems.

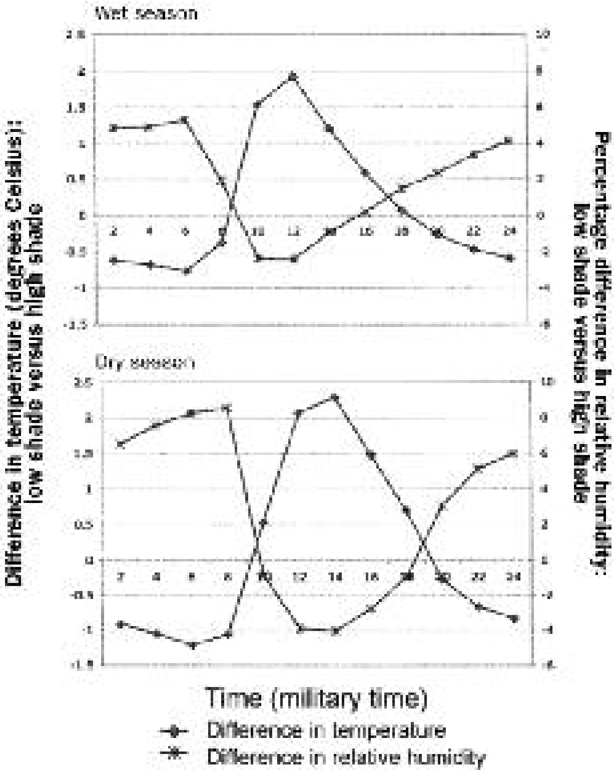

Figure 2. Average difference in temperature (degrees Celsius) and relative humidity (percentage) between low-shade and high-shade coffee-growing sites throughout the day in the wet and dry seasons. The low-shade site experienced higher temperatures and lower relative humidity than the high-shade site. Adapted from data first presented by Lin (2007).

Conclusions

Climate change studies highlight the urgent need to develop adaptive agroecosystems, because many rural farmers depend on rain-fed subsistence agriculture for their livelihoods (Haile 2005, Verdin et al. 2005). Many of these farmers are already on the edge of survival, and further agricultural vulnerability due to climate change will only exacerbate their situation.

To combat this threat, more research should focus on understanding potential synergies between agricultural intensification and global climate change, as well as on investigating how sustainable agricultural practices may provide agroecological resistance to climate variability and therefore may lower farmers' vulnerability to the impacts of climate change (Eakin 2000, Slingo et al. 2005). Coffee production in Latin America is a prime example of this scenario, because a large number of small producers are dependent on coffee agriculture for a living, and there is a systematic trend toward increased intensification along with an increasing variability in climate.

Examining the ability of agroforestry systems to protect coffee from climate extremes and water loss is a useful avenue for research because the use of shade trees may be an economically feasible way for farmers to protect this crop in times of adverse climate conditions. This solution will be pertinent to many areas of the world where increasing climate change and variation are leading to a gradual loss in water availability.

In agriculture, the necessity for finding appropriate management depends on the trade-offs between production and adaptation. Intensifying a system in a way that increases its vulnerability to climatic variation is unwise, especially when that future is virtually guaranteed to have substantially greater variation than the present. Understanding the potential resistance of agroecological systems will become increasingly important as we attempt to develop more rational regional planning to adapt to a future of increasing climatic extremes.

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