

Resilience in Agriculture through Crop Diversification: Adaptive Management for Environmental Change

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Recognition that climate change could have negative consequences for agricultural production has generated a desire to build resilience into agricultural systems. One rational and cost-effective method may be the implementation of increased agricultural crop diversification. Crop diversification can improve resilience in a variety of ways: by engendering a greater ability to suppress pest outbreaks and dampen pathogen transmission, which may worsen under future climate scenarios, as well as by buffering crop production from the effects of greater climate variability and extreme events. Such benefits point toward the obvious value of adopting crop diversification to improve resilience, yet adoption has been slow. Economic incentives encouraging production of a select few crops, the push for biotechnology strategies, and the belief that monocultures are more productive than diversified systems have been hindrances in promoting this strategy. However, crop diversification can be implemented in a variety of forms and at a variety of scales, allowing farmers to choose a strategy that both increases resilience and provides economic benefits.

Keywords: resilience, climate change, diversified agroecosystems, adaptation, trade-offs

The observation that managed ecosystems often fail to respond smoothly to external changes and pressures has led to greater research on ecological regime shifts, thresholds, and resilience (Folke et al. 2004). Although the idea of building resilience has been studied in a broad range of ecosystems, from coral reefs to forests (Nyström et al. 2000, Chapin 2004), this idea has not been well studied in an especially important system to human society: the agroecosystem. The development of resilient agricultural systems is an essential topic of study because many communities greatly depend on the provisioning ecosystem services of such systems (food, fodder, fuel) for their livelihoods (Altieri 1999). Many agriculture-based economies have few other livelihood strategies (Tilman et al. 2002), and small family farms have little capital to invest in expensive adaptation strategies, which increases the vulnerability of rural, agricultural communities to a changing environment. The challenge for the research community is to develop resilient agricultural systems using rational, affordable strategies such that ecosystem functions and services can be maintained and livelihoods can be protected.

Environmental changes may affect many different aspects of agricultural production. With greater climate variability, shifting temperature and precipitation patterns, and other global change components, we expect to see a range of crop and ecosystem responses that will affect integral agricultural processes. Such effects include changes in nutrient cycling

and soil moisture, as well as shifts in pest occurrences and plant diseases, all of which will greatly influence food production and food security (Fuhrer 2003, Jones and Thornton 2003). These changes are expected to increase abiotic and biotic stress, forcing agricultural systems to function under greater levels of perturbation in the future.

Resilience is defined as the propensity of a system to retain its organizational structure and productivity following a perturbation (Holling 1973). Thus, a resilient agroecosystem will continue to provide a vital service such as food production if challenged by severe drought or by a large reduction in rainfall. In agricultural systems, crop biodiversity may provide the link between stress and resilience because a diversity of organisms is required for ecosystems to function and provide services (Heal 2000). Removing whole functional groups of species or removing entire trophic levels can cause ecosystems to shift from a desired to less-desired state, affecting their capacity to generate ecosystem services (Folke et al. 2004). This effect highlights the possibility that agricultural systems already may be in a less-desired state for the continued delivery of ecosystem services.

Vandermeer and colleagues (1998) elucidated the main issues linking the role of diversity in agroecosystems to functional capacity and resilience. First, biodiversity enhances ecosystem function because different species or genotypes perform slightly different roles and therefore occupy

different niches. Second, biodiversity is neutral or negative in that there are many more species than there are functions; thus, redundancy is built into the system. Third, biodiversity enhances ecosystem function because those components that appear redundant at one point in time may become important when some environmental change occurs. The key here is that when environmental change occurs, the redundancies of the system allow for continued ecosystem functioning and provisioning of services. These three hypotheses are not mutually exclusive and change over time and space; therefore, all linkages between diversity and function may be useful for the long-term maintenance of sustainable agricultural systems.

Biodiversity—which allows for the coexistence of multiple species, fulfilling similar functions, but with different responses to human landscape modification—enhances the resilience of ecosystems (Walker 1995). This concept is linked to the insurance hypothesis (Yachi and Loreau 1999), which proposes that biodiversity provides an insurance, or a buffer, against environmental fluctuations because different species respond differently to change, leading to more predictable aggregate community or ecosystem properties. Such diversity insures the maintenance of a system's functional capacity against potential human management failure that may result from an incomplete understanding of the effects of environmental change (Elmqvist et al. 2003).

The recognition that biodiversity is integral to the maintenance of ecosystem functioning points to the utility of crop diversification as an important resilience strategy for agroecosystems. There can be enormous diversity within agricultural systems, and diversification can occur in many forms (genetic variety, species, structural) and over different scales (within crop, within field, landscape level), giving farmers a wide variety of options and combinations for the implementation of this strategy. Diversification at the within-crop scale may refer to changes in crop structural diversity; for example, using a mixture of crop varieties that have different plant heights. Diversification at the within-field scale may be represented by areas between and around fields where trap crops or natural enemy habitat can be planted. At the landscape scale, diversification may be achieved by integrating multiple production systems, such as mixing agroforestry management with cropping, livestock, and fallow to create a highly diverse piece of agricultural land (table 1; Altieri 1999, Gurr et al. 2003). It is important to recognize that diversity can be created temporally as well as spatially, adding even greater functional diversity and resilience to systems with sensitivity to temporal fluctuations in climate.

Because of the impacts that climate change may have on agricultural production, the need to consider diversified agricultural systems is ever more pressing. The following sections review the current knowledge about agricultural diversity and its ability to protect agriculture from the consequences of climate change, as well as the barriers that remain for its adoption as a climate change adaptation strategy. In the first section, I discuss the advantages of diversified agroecosystems

under a future climate by looking at pest, disease, and plant physiological effects. The second section discusses the barriers to the adoption of diversified agriculture as an adaptation strategy, and the third section examines methods to help farmers optimize diversification strategies to improve resilience and protect agricultural production.

Advantages of diversified agroecosystems

Current knowledge suggests that climate change will affect both biotic (pest, pathogens) and abiotic (solar radiation, water, temperature) factors in crop systems, threatening crop sustainability and production. More diverse agroecosystems with a broader range of traits and functions will be better able to perform under changing environmental conditions (Matson et al. 1997, Altieri 1999), which is important given the expected changes to biotic and abiotic conditions. The following are a few of the major ways that the greater functional capacity of diverse agroecosystems has been found to protect crop productivity against environmental change.

Pest suppression. Pest suppression is a perennial challenge to farmers, and it is a very important ecosystem service. In agricultural systems, as in natural ecosystems, herbivorous insects can have significant impacts on plant productivity. The challenges of pest suppression may intensify in the future as changes in climate affect pest ranges and potentially bring new pests into agricultural systems. It is expected that insect pests will generally become more abundant as temperatures rise as a result of range extensions and phenological changes. This abundance will be accompanied by higher rates of population development, growth, migration, and overwintering (Cannon 1998, Bale et al. 2002). Changes in the distribution and abundance of species and communities are unlikely to occur at the same rates. Migrant pests are expected to respond more quickly to climate change than plants, and they may be able to colonize newly available crops and habitats (Cannon 1998, Bale et al. 2002). However, there are a variety of barriers to range expansions, including such biotic factors as competition, predation, and parasitism from other species (Patterson et al. 1999). Promoting such barriers to range expansion and pest viability will have an immediate negative impact on pest outbreaks and will help protect agricultural production.

Farmers may be able to assist in creating biotic barriers against new pests by increasing the plant diversity of their farms in ways that promote natural enemy abundance. The composition of the plant community, as determined by a farmer, may be described as the planned diversity of the system. Crop diversity is critical not only in terms of production but also because it is an important determinant of the total biodiversity in the system (Matson et al. 1997). With greater plant species richness and diversity in spatial and temporal distribution of crops, diversified agroecosystems mimic more natural systems and are therefore able to maintain a greater diversity of animal species, many of which are natural enemies of crop pests (Altieri 1999). Many examples

Table 1. Examples of diversification in agricultural systems and the potential benefits for farmers under climate change.

Type of diversification	Nature of diversification	Benefit	Examples
Increased structural diversity	Makes crops within the field more structurally diverse	Pest suppression	Strip-cutting alfalfa during harvest allows natural enemies to emigrate from harvested strips to adjacent nonharvested ones (Hossain et al. 2001)
Genetic diversity in monoculture	Growing mixed varieties of a species in a monoculture	Disease suppression	Genetic diversity of rice varieties reduces fungal blast occurrence (Zhu et al. 2000)
Diversify field with noncrop vegetation	Growing weed strips or vegetation banks in and alongside crops	Increased production stability	Increased genetic diversity was positively related to mean income and stability of income (Di Falco and Perrings 2003)
		Pest suppression	Grassland or refugia planted at field margins (beetle banks) were used as overwintering habitat for natural enemies (Thomas et al. 1991)
Crop rotations	Temporal diversity through crop rotations	Pest suppression	Using white and black mustard on the field margins of sweet corn crops trapped pests and prevented them from entering the cornfield (Rea et al. 2002)
		Disease suppression	Alternating cereal crops with broadleaf crops and changing stand densities disrupts the disease cycles (Krupinsky et al. 2002)
Polycultures	Growing two or more crop species and wild varieties within the field; spatial and temporal diversity of crops	Increased production	Manipulating diversity through crop rotations of greater cover crop and nitrogen-fixing crops increased the yield of the primary crop (Smith et al. 2008)
		Disease suppression	Grassland fields planted with multiple species to decrease disease transmission (Mitchell et al. 2002)
		Climate change buffering	More ecologically complex systems with wild varieties and temporal and spatial diversity of crops were able to grow under climate stress (Tengö and Belfrage 2004)
Agroforestry	Growing crops and trees together; spatial and temporal diversity	Increased production	Grassland plots with greater in-field species diversity led to more stable feed and fodder production (Tilman et al. 2006)
		Increased production	Grassland plots with greater in-field species diversity led to increased production (Picasso et al. 2008)
		Pest suppression	Willow trees grown in natural willow habitats experience lower rates of pest outbreak of the leaf beetle (Dalin et al. 2009)
		Pest suppression	Greater shade diversity increased bird natural enemy abundance for larval control on crop plant (Perfecto et al. 2004)
		Pest suppression	Coffee berry borer control increased with greater ant diversity and abundance in shade systems (Armbrecht and Gallego 2007)
Mixed landscapes	Development of larger-scale diversified landscapes with multiple ecosystems	Climate change buffering	Greater shade cover led to increased buffering of crop to temperature and precipitation variation (Lin 2007)
		Climate change buffering	Greater shade tree cover led to increased buffering from storm events and decreased storm damage (Philpott et al. 2008)
		Pest suppression	Complex landscapes that have areas of woodland and hedgerows interspersed within fields had higher rates of larval parasitism (Marino and Landis 1996)
		Pest suppression	Oilseed rape crops adjacent to complex, structurally rich, and large old fallows had higher rates of parasitism by the rape pollen beetle (Thies and Tscharrntke 1999)
		Increased production	Mixed land use of organic cropland, crop rotations, and intensive managed grazing led to optimal diversity and profitability strategies (Boody et al. 2009)

of pest suppression have been shown within agricultural systems possessing diversity and complexity, especially in comparison with less-complex systems (Cannon 1998). For example, in willow systems, insect pest outbreaks of the leaf beetle *Phratora vulgatissima* have been shown to be greater in willow monocultures than in natural willow habitats (Dalin et al. 2009). However, in a review of specialist and

generalist natural enemy responses to agricultural diversification, it was found that diversification may reduce natural enemy searching efficiency. Moreover, pest control by specialist enemies may be less effective in a more diverse agroecosystem because a lower concentration of host plants may reduce attraction or retention of these specialist enemies (Sheehan 1986).

Habitat management is one method used within agricultural systems to alter habitats to improve the availability of the resources natural enemies require for optimal performance (Landis et al. 2000). Such management techniques have been developed for use at within-crop, within-farm, or landscape scales, and some have been proven to be very economical for farmers. In one review examining pest management in agriculture (Gurr et al. 2003), the authors found that many degrees of complexity exist in increasing biodiversity for pest management. Simply diversifying the plant age structure of a monoculture or strip-cutting fields such that natural enemies have a temporal refuge can improve in-field habitats for natural enemies. Larger-scale changes, such as integrating annual and perennial noncrop vegetation; increasing crop diversity within the field; or increasing farmwide diversification with silviculture, agroforestry, and livestock may also provide a variety of other functions to the system (table 1; Gurr et al. 2003).

In an example from a meta-analysis of the density response of natural enemies (invertebrate predators and parasitoids) to experimental changes in structural complexity, Langelotto and Denno (2004) found that increasing structural complexity led to a significant rise in natural enemy abundance at habitat and within-plant scales. Hunting and web-building spiders showed the strongest response to structural complexity, followed by hemipterans, mites, and parasitoids. Evidence of greater spider abundance in response to diversification has also been shown by Sunderland and Samu (2002), who found that abundance increased with structural complexity in 63% of the studies they examined. The central conclusion of this review was that spiders tend to concentrate in diversified patches, and greater diversification throughout the whole crop would offer the best prospect of improving pest control (Sunderland and Samu 2000).

One example of a perennial system that exhibits a rich range of natural enemy pest control is the coffee agroforestry system, where there is a wide variety of spatial and temporal diversity determined by the shade trees planted within the cropping system. Greater natural enemy presence has been observed in the more diverse and shaded agroforestry systems, and increased bird diversity and density have been shown to reduce herbivore plant damage through greater insectivorous bird predation (Perfecto et al. 2004). It has also been observed that predatory ground-dwelling ants are attracted to and prey upon the coffee berry borer, a major pest of coffee production, with greater efficiency in diversified coffee systems when compared with unshaded monocultures (Armbrecht and Gallego 2007).

The integration of diversified systems into agriculture can have financial benefits for the farmer, as well. One financially beneficial type of habitat management that has been widely adopted at the within-field scale is the beetle bank, where native grasslands and refugia are maintained at the field margins to protect carabid beetle populations. In one analysis of the costs and benefits associated with pest suppression, the

cost of establishing a beetle bank in a 20-hectare (ha) wheat field, combined with yield loss resulting from land removed from production, was calculated at \$130 for the first year with subsequent costs and yield losses of \$45 per year. However, the ability to keep aphid populations below a spray threshold through natural enemy suppression saved about \$450 per year in labor and pesticide costs, and the prevention of aphid-induced yield loss saved about \$1000 per year for the 20-ha field. These figures show that the loss in productive land for the establishment of the beetle banks was more than offset by the money saved from reduced pesticide use and aphid-induced yield loss (Thomas et al. 1991).

Although climate change may produce a shift in pest and natural enemy ranges, an agricultural system with greater plant biodiversity improves the system's resilience by harboring greater natural enemy biodiversity, thereby protecting crops from a large variety of potential future pests. Although natural enemies in a diverse system may be functionally redundant at the present, they may no longer prove redundant as future changes occur. The diversity of plant species within the agroecosystem therefore provides long-term pest suppression for agricultural systems by building up a bank of potential natural enemies for any future pest outbreaks in the system.

Disease suppression. Losses caused by pathogens can contribute significantly to declines in crop production, and changes in climate potentially could affect plant disease distribution and viability in new agricultural regions. From 2001 to 2003, 10% of the global crop losses in wheat, rice, and maize were shown to be a result of pathogens (Oerke 2006).

The diversity of crop species in an agroecosystem has a much less predictable effect on microbial pathogens compared with crop pests, as microclimatic conditions play an important role in the development and severity of a disease (Matson et al. 1997, Fuhrer 2003). The effect of climate change on disease prevalence is therefore much less certain. Climate change could have positive, negative, or no impact on individual plant diseases (Chakraborty et al. 2000), but it is suspected that milder winters may favor many crop diseases, such as powdery mildew, brown leaf rust, and strip rust, whereas warmer summers may provide optimal conditions for other diseases, such as cercospora leaf spot disease (Patterson et al. 1999). Global change is also predicted to alter the distribution and abundance of arthropod vectors that distribute viruses, thereby affecting the rates of and chances for crop transmission (Anderson et al. 2004).

A central tenet of epidemiology is that both the number of diseases and the incidence of disease should increase proportionally to host abundance (Tilman et al. 2002). In one grassland study, in which grassland plant species richness and composition were manipulated, the pathogen load was almost three times greater in the monoculture plots, where host abundance was at a maximum, than in the polyculture plots planted with 24 grassland species (an approximation of natural diversity; Mitchell et al. 2002). Eleven diseases

were more severe at lower plant species richness, with most of the diseases correlating with host abundance, showing that the greater abundance of host species within lower-species-diversity plots increased disease transmission.

The loss of genetic diversity in crop production has led to a hypothesized increase in crop disease susceptibility as a result of higher rates of disease transmission. Many mechanisms reduce the spread of disease in agricultural systems with greater varietal and species richness. Barrier and frequency effects occur when other disease-resistant varieties or species block the ability of a disease or virus to transmit and infect a susceptible host (Finckh et al. 2000). These effects increase with greater spatial and temporal diversity in the agricultural system, and intentional crop system diversity with greater barrier effects can significantly reduce pathogen impacts on crop production. Multiline cultivars and varietal mixtures have been used to effectively retard the spread and evolution of fungal pathogens in small grains and to control some plant viruses (Matson et al. 1997).

One well-known example of barrier effects in rice production showed that genetic variation within species and within populations can increase the ability of an agricultural system to respond to pathogen diseases. Zhu and colleagues (2000) demonstrated that in-field genetic crop heterogeneity suppresses disease in rice crops suffering from rice blast. Disease-susceptible rice varieties, when planted in mixtures with resistant varieties over large tracts of land, had 89% greater yield and 94% reduced fungal blast occurrence than when planted in monoculture. Because of this experiment's success, fungicidal sprays were no longer applied to these fields after the trial. Rather, farmers grew rice in mixtures in order to improve the resilience of the systems while reducing economic costs. There have been few such large-scale experiments to study the efficacy of genetic heterogeneity to increase production, reduce chemical use, and potentially stabilize or even reduce food prices for a region, but these results do provide evidence that intraspecific crop diversification has the potential to effectively control fungal disease spread and protect against crop loss.

Increasing diversification of cereal cropping systems by alternating crops, such as oilseed, pulse, and forage crops, is another option for managing plant disease risk (Krupinsky et al. 2002). Disease cycles could be interrupted through crop rotation by interchanging cereal crops with broadleaf crops that are not susceptible to the same diseases. Reduced tillage could enhance soil biodiversity, leading to greater disease suppression, and stand densities could be adjusted to allow for better microclimatic adjustments to disease growth.

These examples show that farmers can take advantage of greater crop diversification to reduce disease susceptibility in agricultural systems, thereby limiting the amount of production loss as a result of crop diseases. Although changes in disease spread and severity are uncertain under climate change, greater genetic variation across space and time could potentially reduce adverse disease transmission impacts that may accompany climate change.

Climate variability buffering and mitigation. Diversified agroecosystems have become more important for agriculture as climate fluctuations have increased. Research has shown that crop yields are quite sensitive to changes in temperature and precipitation, especially during flower and fruit development stages. Temperature maximums and minimums, as well as seasonal shifts, can have large effects on crop growth and production. Greater variability of precipitation, including flooding, drought, and more extreme rainfall events, has affected food security in many parts of the world (Parry et al. 2005).

Agricultural vulnerabilities have been found in a number of important crop species. Observations of rice production in the Philippines during an El Niño drought season showed reductions in seed weight and overall production (Lansigan et al. 2000). Studies of wheat have demonstrated that heat pulses applied to wheat during anthesis reduced both grain number and weight, highlighting the effect of temperature spikes on grain fill (Wollenweber et al. 2003). In maize, researchers observed reduced pollen viability at temperatures above 36 degrees Celsius, a threshold similar to those in a number of other crops (Porter and Semenov 2005).

Such observed agricultural vulnerabilities to changes in temperature and precipitation point to the need to develop resilient systems that can buffer crops against climate variability and extreme climate events, especially during highly important development periods such as anthesis. There are a variety of ways that diversified agricultural systems exemplify that more structurally complex systems are able to mitigate the effects of climate change on crop production.

Agroforestry systems are examples of agricultural systems with high structural complexity. Although the primary crop of interest (e.g., coffee, cacao) is sometimes grown in more intensively managed systems with little shade cover, the more structurally complex systems have been shown to buffer crops from large fluctuations in temperature (Lin 2007), thereby keeping crops in closer-to-optimal conditions. The more shaded systems have also been shown to protect crops from lower precipitation and reduced soil water availability (Lin et al. 2008) because the overstory tree cover reduces soil evaporation and improves soil water infiltration.

Agroforestry systems also protect crops from extreme storm events (e.g., hurricanes, tropical storms) in which high rainfall intensity and hurricane winds can cause landslides, flooding, and premature fruit drop from crop plants. In one example from Mexico, greater farming intensity of coffee agroforestry systems was correlated with the percentage of farm area lost to landslides and the amount of coffee production lost to premature fruit drop (Philpott et al. 2008). In another example of diverse agriculture systems and hurricanes, a study of Nicaraguan farms following Hurricane Mitch in 1998 showed that less intensively managed land, which exhibited greater diversity and structural complexity, suffered less erosion, had more vegetation, and experienced lower economic losses from hurricane damage (Holt-Giménez 2002). Resistance patterns became more

apparent in areas with high storm intensity, and complex interactions and thresholds exist, but are difficult to detect.

In a comparative study of farming systems in Sweden and Tanzania, two locations where agriculture has suffered from climate variation and extreme events, it was found that agricultural diversity increased the resilience of the production systems. Sweden suffered from cold-tolerance issues, whereas Tanzania suffered from problems of heat tolerance and irregular El Niño cycles. Both locations experienced greater seasonal drought. In these cases, research showed that successful management practices able to buffer systems from climate variation and protect production were those that were generally more ecologically complex, incorporating wild varieties into the agricultural system and increasing the temporal and spatial diversity of crops (Tengö and Belfrage 2004).

These examples present a potential long-term strategy for farmers experiencing patterns of reduced rainfall and growing temperature variability. Diversification of agricultural systems can significantly reduce the vulnerability of production systems to greater climate variability and extreme events, thus protecting rural farmers and agricultural production.

Barriers and challenges to the increased adoption of diversified agriculture

Although many recognize that diversity can improve the resilience of agricultural systems to environmental change, the adoption of increased diversification has been slow for a number of reasons. First, economic policy incentives for the production of monoculture row crops under intensive management have outweighed the perceived incentives to implement diversified farming systems, although this may change as climatic variations increase. Second, many of the efforts to adapt agriculture to climate change have focused on the development of biotech solutions to produce drought-resistant crops, pushing agriculture toward more expensive and intensive forms of management. Lastly, the mistaken belief that biomass production is substantially greater in monocropped systems than in multispecies systems has discouraged the move toward more diversified systems. Such barriers slow the rate of adoption of diversified agricultural systems as adaptation options and must be addressed in order to hasten the implementation of this strategy.

Farm price and income supports: A US example. In the United States, the economic incentives to intensify production in monoculture systems outweigh the incentives to diversify agriculture systems. Agricultural subsidies select mainly for five crops—corn, wheat, soybean, cotton, and rice—thereby incentivizing greater production of these few crops. Between 1995 and 2002, 89% of the \$91.2 billion disbursed in commodity payments went to these crops in order to boost the income of crop and livestock farmers. Soybean and corn farmers alone received 56% of that money (Boody et al. 2009). The commodity payment system encourages

monocropping of select crops because payments are determined by acreage of crop produced, thereby incentivizing the maximum production of one or a few crops over large tracts of landscape. Such incentives favor greater production of fewer species planted in space and time, at the expense of ecosystem services and ecosystem function (Altieri 1999, Tilman et al. 2002).

Incentives for the greater production of fewer crops have also been supported by the mechanization of many agricultural production practices (e.g., planting, harvesting). Mechanization is now the status quo in the United States and is necessary for this type of production system. The mechanization of crop species for maximum production, in general, is most efficient when only one crop is planted because management systems (e.g., planters, harvesters, chemical inputs, irrigation systems) can be designed for one crop type and one crop structure, thereby decreasing labor time and costs (Pimentel et al. 2008). In this sense, an agricultural system that selects mainly for one or two main crops and is highly mechanized can be very efficient and productive, and certainly this ability to scale up production and increase yield has had many advantages for food production and the maintenance of stable food prices in the past.

However, farm price and income supports were originally developed because farm households were financially disadvantaged compared with other US households, not to increase the production of specific crops. Current data show that farm household incomes have risen above those of the average nonfarm household (Mishra and Sandretto 2002), and that much of the subsidy program does not support small farmers; rather, the majority of the money goes to large farms that own wide swaths of land (Riedl 2007), thereby negating the original intent of the price- and income-support mechanisms. This brings into question the true economic benefit of subsidies for many small farmers, who will be most vulnerable to climate change-induced production losses in the future. Incentives that can increase economic productivity of farms by permitting the selling of ecosystem services, such as carbon sequestration, have the potential to increase the adoption of diversified farm systems such as terraces and agroforestry (Antle et al. 2007). Developing policy that incentivizes the diversification of agricultural crops and landscapes may be a more rational strategy for developing resilient agricultural systems and protecting food production in the future under climate change (Boody et al. 2009).

Biotech solutions. The recognition that agriculture will face challenges under climate change has brought about a major effort to adapt agriculture through technical means, primarily the research and development of drought-resistant biotech crops. The push for greater use of biotechnology that focuses on sole-crop agriculture has made some headway in protecting production yields for some farmers, but it has not succeeded in many situations, especially in developing nations (Herdt 2006). Yet biotech continues to be a major

focus in agricultural adaptation solutions to climate change. According to assessments by the Australian government, crops genetically engineered for drought tolerance have not been found to outperform traditional varieties (Braidotti 2008), and in fact, many traits are most easily bred into crop systems using conventional breeding through crop genetic diversity (USDA 2008). The authors of an International Water Management Institute report (IWMI 2007) concluded that improvements in biotech products would have only a moderate impact over the next 15 to 20 years in making crops more efficient in using water. They also concluded that “greater, easier, and less contentious gains” could come from managing water supplies better, rather than trying to develop crops that can flourish with less water (IWMI 2007).

Additionally, the speed of research and development of new biotech crops must be assessed in comparison with the speed of climate change effects on agriculture. A recent *New York Times* article (Pollack 2008) that interviewed a researcher on Monsanto drought-tolerant corn stated that drought-tolerant varieties could reach American farmers in four years, with a 10% increase in yield. Other varieties could reach Africa by 2017 (Pollack 2008). The difficulty with assessing such scenarios is the uncertainty in the rate of change that farmers will have to contend with in the next 5 to 10 years. Will the technology developed today be sufficient to protect farmers under the climate conditions of the future when it is launched in 5 to 10 years? For how long will the technology be useful? Such products may also be prohibitively expensive, which will pose a challenge for smallholder rural farmers who may want to pursue this adaptation option under climate change.

If there is indeed a temporal scale mismatch in the rate of development of adequate biotech lines and the rate and extent of climate change effects on agriculture, farmers will have to turn to other adaptation options to improve the resilience of their systems to climate change. The need to develop options for present and expected climate change and for those who will have no access to such technology remains a great problem for agricultural development and food security fields. Diversified agriculture in such cases remains a highly accessible adaptation option for many farmers.

Biomass production. The belief that monocultures and intensively managed systems are more productive than diversified agricultural systems is another challenge to moving agricultural systems toward more diversity. Maximizing biomass production of one or two specific crops is essentially the goal of the current modern agricultural paradigm. Although ecosystem functioning of such systems persists at much reduced capacity, outside infrastructure such as mechanization, chemical inputs, and irrigation systems can help replace the lost functionality (Altieri 1999) to enable high production. However, the potential effects of climate change on agriculture stability will further complicate our predictions of production and pricing of goods from large-scale, monocropped systems.

In many regions of the world, the ability to use intensified production practices and products is limited by cost and transportation. Petroleum for mechanization techniques and chemical inputs can be prohibitively expensive. Even in regions with access to mechanization and chemical inputs, a lack of water resources can severely reduce production capacity. In such cases, diversified agricultural systems that are able to produce under extreme climate scenarios are preferable because many of the ecosystem functions that cannot be brought into the system through inputs and mechanizations can be provided through natural means. Such solutions support both biodiversity and community resilience to climate change by taking advantage of ecosystem functions and services, supporting high production yields in potentially adverse environmental conditions.

A variety of research has shown that high plant diversity within agricultural plots can yield higher production levels than systems with low plant diversity. Grassland experiments have shown that greater plant species diversity is correlated with greater temporal stability in annual aboveground plant production, demonstrating that a more efficient and sustainable supply of food, such as fodder, can be enhanced by increasing biodiversity (Tilman et al. 2006). In a study examining the effect of species diversity on crop and weed biomass in perennial herbaceous polycultures, biomass increased log linearly with species richness and polycultures outyielded monocultures by an average of 73% (Picasso et al. 2008). A growth in production has also been seen in field experiments manipulating diversity in crop rotations (crops, cover crops, and chemical inputs), showing significantly greater corn grain yields with increased diversification over time (Smith et al. 2008). Such results demonstrate that diverse polycultures can have higher and more stable yields that lead to increased economic benefits for farmers as well.

However, not all studies have shown that greater diversity leads to increased production yield. In one study, biodiverse rotational systems of three to six species produced 25% lower yield versus integrated monocropped grain systems, but the grain was of higher quality. The high-quality grain from the more biodiverse system must be of greater value to overcome the economic benefit of higher production in the lower-quality monoculture (Snapp et al. 2010).

Developing optimization strategies and win-win solutions for diversification

A major challenge for the implementation of diversified agricultural systems for farmers is finding the appropriate balance of diversification within the farm system to satisfy both production and protection values. Farmers and agricultural managers must consider the variety of ways that diversification can occur within the system and develop methods that best meet their specific needs of crop production and resilience. Of course, as climate change variability increases, the value of resilience will also increase, especially in production systems sensitive to climate variation. However, a farmer’s decision to move toward diversified

agricultural systems will be highly influenced by the ability of the diversification strategy to support the economic resilience of farms. Cost-cutting examples, such as the use of beetle banks to reduce pesticide costs (Thomas et al. 1991) or the reduction of fungicide use in integrated rice systems (Zhu et al. 2000), illustrate the significant possible economic benefits of greater biodiversity. Policy incentives that strongly promote adaptation are also necessary for transitioning agriculture to a long-term sustainable state. Finding win-win solutions that account for farmers' various production and protection goals is necessary to develop long-term, viable strategies.

Optimizing diversification strategies at various scales. Developing tools that can help managers understand best practices on a farm field or landscape scale can significantly enhance diversity in agricultural systems while increasing the resilience of systems to climate change and maintaining high yields.

At the farm field level, techniques such as crop modeling (e.g., Decision Support System for Agrotechnology Transfer [Jones et al. 2003], Agricultural Production Systems Simulator [Keating et al. 2003]) allow researchers to simulate crop mixtures within a specific regional setting in order to model crop thresholds and production levels to climate and management variables. Such systems can be very powerful for modeling crop outcomes under climate change scenarios, as climate data can be adjusted to mimic greater climate variation as well as any accompanied changes in agricultural farm management (e.g., crop mixtures and rotations; Weiss et al. 2003). However, accurate modeling of agricultural systems requires extensive knowledge of on-the-ground parameters, such as soil profiles for water and nutrient distribution, as well as a variety of crop-specific physiological development data usually gained through field trials. This information can be difficult to obtain, as it requires labor and technical understanding to collect the appropriate data.

However, it will greatly benefit future planning if there is greater development of extension and on-the-ground research staff who are able to assist in collecting relevant soil and plant development data and in modeling cropping strategies to specific location variables. Simulation analyses conducted on specific production scenarios are especially useful in improving decisionmaking (e.g., what crops should be planted, and when), particularly when performed in conjunction with local knowledge of potential environmental and socioeconomic challenges. The use of interdisciplinary research to consider the overall crop management system will allow for better adaptation method development and implementation (Stone and Meinke 2005).

Because farmers require economic incentives to be willing and able to adopt new practices, economic models that can predict threshold prices at which farmers begin to adopt environmental land-use practices or payments for ecosystem services can be highly effective in encouraging farmer

adoption of diversified agricultural systems. In one model of the potential of farmers to participate in carbon sequestration contracts and increase sequestration potential through agroforestry and terracing of fields, analysis showed that at prices higher than \$50 per metric ton of carbon, adoption would increase substantially, and at prices of \$100 per metric ton of carbon, terrace and agroforestry adoption for carbon sequestration would have the potential to raise per capita incomes by up to 15% (Antle et al. 2007). Such economic models are also helpful for understanding whether price incentives are effective for a particular goal. In a study by Wu and colleagues (2004) of price incentives for agriculture conservation practices in order to reduce nutrient and soil pollution of the Mississippi River, an economic model showed that payments of \$50 per acre for conservation tillage and crop rotation increased the adoption of these conservation practices but were limited in their potential to reduce hypoxia, the ultimate goal. Such results allowed policymakers to concentrate on alternate conservation options and incentives that would have a larger impact on the ultimate goal of reducing hypoxia (Wu et al. 2004).

Development of larger-scale diversified landscapes that support and improve ecological resilience in agricultural systems requires a more in-depth analysis of the farm business and landscape-level scenario modeling for on-farm diversity possibilities. For example, Boody and colleagues (2009) examined how two watersheds in Minnesota would fare under a variety of future land-use scenarios including (a) a continuation of current trends, (b) the application of best management practices (BMPs) over the landscape, (c) a mixture of agricultural uses that maximize diversity and profitability, and (d) a scenario increasing vegetative cover over the landscape (Boody et al. 2009). The scenario that maximized on-farm diversity and profitability moved beyond BMPs alone and included organic cropland, five-year crop rotations, and intensive managed grazing. This diverse system increased profits and biodiversity while reducing environmental externalities (e.g., water quality, greenhouse gases, sedimentation, and flooding), thereby creating a win-win-win solution. Such scenario modeling of landscapes could be very useful for farmers making decisions about large tracts of land or in systems where there is a cooperative structure in land management. These types of modeling scenarios may also assist decisionmakers in long-term planning of landscapes.

Stakeholder involvement and participatory research. The adoption of sustainable agricultural options under climate change has been a challenge for many communities, as the idea of climate change adaptation can seem overwhelming. The ability and space to communicate adaptation options is very important to implementation success; discussing the risk and uncertainty of climate change is especially critical, as sound climate science is required to implement rational and useful strategies. Additionally, stakeholders must understand that adaptation options become fewer as climate variability

increases; the cost and complexity of adaptation will increase, yet the benefits of adaptation will increase as well (Howden et al. 2010).

Stakeholder involvement and participatory research are often very useful tools in developing adaptation options that will be adopted by a local community because these methods recognize that knowledge often lies with the farmers in the field, and that local considerations should be integrated into long-term planning (Rivington et al. 2007). In Australia, the Commonwealth Scientific and Industrial Research Organisation engages with rural agricultural communities through agricultural stakeholder meetings to discuss the effect of climate variability on challenges and priorities for local farmers. Farmers are active participants in developing adaptation solutions, such as the modeling scenarios of on-farm crop mixtures and rotations. Because of stakeholder engagement, farmers develop ownership of solutions and therefore more readily adopt adaptation strategies onto their farms (Gardner et al. 2009). Thus, partnerships among stakeholders (farmers and scientists) are necessary for the successful development and adoption of sustainable management, such as the use of simulation approaches to help farmers find optimal strategies.

Conclusions

It is abundantly clear that farmers are facing growing stress from climate change, and that the greater implementation of diversified agricultural systems may be a productive way to build resilience into agricultural systems. The challenges to increasing adoption of diversified agricultural management strategies are both scientific and policy based. In the scientific realm, the adoption of diversified agricultural systems could be bolstered if farmers had a better idea of how to optimize a diversified structure to maximize production and profits. Crop and landscape simulation models that can model a range of climate scenarios and landscape modeling with farm profitability scenarios would help farmers find optimal strategies for maintaining production and profit. Stakeholder-based participatory research would also be highly beneficial, as researchers could model strategies that seem plausible to farmers.

In the policy realm, diversification within agricultural systems could potentially increase in the United States through the adjustment of the farm income support systems to incentivize more diverse cropping systems that support small farmers. Internationally, diversified agriculture can have a large role in protecting food security and production in regions where farmers have little access to chemical, structural, or technological resources. Diversified farming strategies are supported by international research efforts, including the International Assessment on Agricultural Knowledge, Science and Technology for Development, a global report of more than 400 scientists that concluded that locally adapted seed and ecological farming better addressed the complexities of climate change, hunger, poverty and productive demands on agriculture in the developing world. The report also showed that the ecological processes of these

more complex systems could be used to protect farmers from climatic change and improve food security.

Understanding the potential of increasing diversity within farm systems is essential to helping farmers adapt to greater climate variability of the future. By adopting farm systems that promote ecosystem services for pest and disease control and resilience to climate change variability, farmers are less at risk to production loss and are more generally resilient to environmental change.

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