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REVIEW ARTICLE

Agroecology and the design of climate change-resilient farming systems

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Abstract Diverse, severe, and location-specific impacts on agricultural production are anticipated with climate change. The last IPCC report indicates that the rise of CO_2 and associated "greenhouse" gases could lead to a 1.4 to 5.8 °C increase in global surface temperatures, with subsequent consequences on precipitation frequency and amounts. Temperature and water availability remain key factors in determining crop growth and productivity; predicted changes in these factors will lead to reduced crop yields. Climate-induced changes in insect pest, pathogen and weed population dynamics and invasiveness could compound such effects. Undoubtedly, climate- and weather-induced instability will affect levels of and access to food supply, altering social and economic stability and regional competiveness. Adaptation is considered a key factor that will shape the future severity of climate change impacts on food production. Changes that will not radically modify the monoculture nature of dominant agroecosystems may moderate negative impacts temporarily. The biggest and most durable benefits will likely result from more radical agroecological measures that will strengthen the resilience of farmers and rural communities, such as diversification of agroecosytems in the form of polycultures, agroforestry systems, and crop-livestock mixed systems accompanied by organic soil management, water conservation and harvesting, and general enhancement of agrobiodiversity. Traditional farming systems are repositories of a wealth of principles and measures that can help modern agricultural systems become more resilient to climatic extremes. Many of these agroecological strategies that reduce vulnerabilities to climate variability include crop diversification, maintaining local genetic diversity, animal integration, soil organic management, water conservation and harvesting, etc. Understanding the agroecological features that underlie the resilience of traditional agroecosystems is an urgent matter, as they can serve as the foundation for the design of adapted agricultural systems. Observations of agricultural performance after extreme climatic events (hurricanes and droughts) in the last two decades have revealed that resiliency to climate disasters is closely linked to farms with increased levels of biodiversity. Field surveys and results reported in the literature suggest that agroecosystems are more resilient when inserted in a complex landscape matrix, featuring adapted local germplasm deployed in diversified cropping systems managed with organic matter rich soils and water conservation-harvesting techniques. The identification of systems that have withstood climatic events recently or in the past and understanding the agroecological features of such systems that allowed them to resist and/or recover from extreme events is of increased urgency, as the derived resiliency principles and practices that underlie successful farms can be disseminated to thousands of farmers via *Campesino a Campesino* networks to scale up agroecological practices that enhance the resiliency of agroecosystems. The effective diffusion of agroecological technologies will largely determine how well and how fast farmers adapt to climate change.

Keywords Agroecology · Climate change · Resilience · Adaptive capacity

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1 Introduction

The recent 2013 report of the IPCC (2014) authoritatively re-affirms that climate change and variability will impact food and fiber production around the world due to the effects on plant growth and yield by elevated CO_2, higher temperatures, altered precipitation and transpiration regimes, and increased frequency of extreme events, as well as modified weed, pest, and pathogen pressure (Lobell et al. 2011). Although modeling studies suggest increasing frequency of crop loss due to climatic variability and the increased frequency of *extreme events* such as droughts and floods or changes in precipitation and temperature variance, impacts on food systems at the global scale might be relatively small overall in the first half of the 21st century (Adams et al. 1998). Effects however will be progressively negative after that. Conventional wisdom states that crop production in (mainly low latitude) developing countries would suffer more, and earlier, than in (mainly mid- to high latitude) developed countries, due to a combination of adverse agroclimatic, socio-economic, and technological conditions (Rosenzweig and Hillel 2008).

Due to these impacts, climate change alone is estimated to increase the number of undernourished people to between 40 million and 170 million. Moreover, the effects of progressive increases in global mean temperatures will successively lead to a pronounced increase in food prices (as much as 30 %), which in turn will lead to more frequent social upheavals as witnessed during the 2008's food riots (Hillel and Rosenzweig 2009). Undoubtedly, climate- and weather-induced instability in food and fiber will alter social and economic stability and regional competiveness (Ziska and Dukes 2014).

These findings suggest two important realities: (a) because agriculture relies greatly on adequate water, temperature, and a delicate balance of gases such as carbon dioxide and methane in the atmosphere, farming is the human endeavor most vulnerable to the effects of climate change and (b) climate change and global food security are inextricably linked. The tragedy is that 80 % of the world's arable land is increasingly being planted with a handful of crop commodities (corn, soybean, wheat, rice, and others), therefore dangerously narrowing the genetic diversity present in global agricultural systems (Adams et al. 1971). The majority of these crops are grown under "modern monoculture systems" which due to their ecological homogeneity are particularly vulnerable to climate change as well as biotic stresses, a condition that constitutes a major threat to food security (Heinemann et al. 2013).

Clearly, dominant current monocropping production systems will need to adapt to meet these changing pressures associated to the frequency and intensity of extreme weather. Adaptation is considered a key factor that will shape the future severity of climate change impacts on food production. But this will depend on the kinds of adaptation strategies that will be used. Changes that will not radically modify the monoculture nature of dominant agroecosystems such as shifting planting dates, switching or introducing new crop varieties, and expanding and improving irrigation may moderate negative impacts temporarily (Matthews et al. 2013). The biggest and most durable benefits will likely result from more radical agroecological measures including the diversification of agroecosytems in the form of polycultures, agroforestry systems, and crop-livestock mixed systems accompanied by organic soil management, water conservation and harvesting, and general enhancement of agrobiodiversity. In this paper, we contend that what is needed is an agroecological transformation of monocultures by favoring field diversity and landscape heterogeneity, a strategy that represents a robust path to increasing the productivity, sustainability, and resilience of agricultural production while reducing undesirable socio-economic and environmental impacts due to climate change (Altieri 2002; de Schutter 2010).

2 The effects of climate change on agricultural production

There is an immense literature that analyzes the impacts that global warming will have on crop growth and production (Kurukulasuriya and Rosenthal 2003; Easterling et al. 2007; Lobell and Gourdji 2012). Although authors offer different scenarios, the consensus is that the productivity of crops and livestock may decline because of high temperatures and drought-related stress, but these effects will vary among regions. Diverse and location-specific impacts on agricultural production are anticipated. While the global agricultural supply is likely to be robust in the face of moderate climate change, severe regional variation is expected. Regions at mid- to high latitudes (where global warming will extend the length of the potential growing season) may not experience the yield decreases expected in tropical regions which are expected to be the worst affected from climate change, suffering significant agricultural production losses (Fig. 1). Many of these countries are also currently under severe economic and ecological stress. Climate change is expected to push the agricultural sectors in these countries into further hardship. Historical studies demonstrate that climate change has already had negative impacts on crop yields. Maize, wheat, and other major crops have experienced significant climate-associated yield reductions of 40 million tons per year from 1981 to 2002 at the global level (Lobell et al. 2011). Jones and Thornton (2003) projected a reduction of around 10 % in maize production in Africa and Latin America under various climate scenarios to 2055, corresponding to losses of US$2 billion per year.

Changes in total seasonal precipitation or in its pattern of variability will also impact crop production, but most models assert that the majority of impacts are mostly driven by trends in temperature rather than precipitation. Changes in yields of rainfed crops will be driven by changes in both precipitation and temperature, while changes in yields on irrigated land will be driven by temperature changes alone. Warmer temperatures may make many crops grow more quickly, but warmer temperatures could also reduce yields of certain crops (Fig. 2). For any particular crop, the effect of increased temperature will depend on the crop's optimal temperature for growth and reproduction; in areas where warming exceeds a crop's optimum temperature, yields can decline (Lobell and Field 2007).

The demand for water for irrigation is projected to rise in a warmer climate, which will increase evaporation from the soil and accelerate transpiration in the plants, bringing increased competition between agriculture and urban as well as industrial users. An increase of potential evapotranspiration is likely to intensify drought stress, especially in the semiarid tropics and subtropics; therefore, these rainfed regions (89 % of cereals in sub-Saharan Africa are rainfed) may require irrigation, bringing higher costs and conflict over access to water (Döll 2002). Falling water tables and the resulting increase in the energy needed to pump water will make the practice of irrigation more expensive, particularly when with drier conditions more water will be required per acre.

Climate is a significant driver of pest population dynamics; especially temperature has a strong and direct influence on insect development, reproduction, and survival. No doubt climate change will require adaptive management strategies to cope with the altered status of pests and pathogens. Some researchers expect that certain insect pests, diseases, and weeds may survive or even reproduce more often each year if cold winters no longer keep them in check. Longer growing seasons will enable certain insect pests to complete a greater number of reproductive cycles during the spring, summer, and autumn (Porter et al. 1991). Warmer winter temperatures may also allow larvae to overwinter in areas where they are now limited by cold, thus causing a greater infestation during the following crop season. New pests may also invade new regions as temperature and humidity conditions change. For example, lower-latitude pests may move to higher latitudes.

Fig. 1 In tropical regions, increased precipitation will lead to flooding with serious effects on crop production as illustrated with this banana plantation in the Colombian Choco region

Fig. 2 Droughts will severely affect the production of dry-farmed crops, such as this maize (maiz de temporal) in the Mixteca region of Mexico

Moreover, altered wind patterns may change the spread of both wind-borne insect pests and of bacteria and fungi that are the agents of many crop diseases (Coakley et al. 1999). Predicted climatic changes are expected to mediate range expansion of invasive species, which constitute agricultural, forestry, stored product, household, and structural pests and can be parasites or vectors of diseases. This is of particular concern with insects, which, in addition to leading to major crop losses, have the potential to impact on native biodiversity. In North America, invasive insects already make up 40 % of the major insect pest species, even though they represent only 2 % of the total insect fauna (Ward and Masters 2007).

A hierarchy of analytical tools is required to conduct risk assessments, inform policy, and design pest management on scales from regions to landscapes and fields. Such tools include models for predicting potential geographical distributions, seasonal phenology, and population dynamics at a range of spatial and temporal scales (Sutherst et al. 2011). For example Ponti et al. (2014) estimated the effects of climate change on the dynamics and interaction of olive and the olive fruit fly using physiologically based demographic models in a geographic information system context as driven by daily climate change scenario weather. In their assessment of climate change impact on olive agroecosystems, they analyzed trophic interactions, which include the effects of climate change on olive phenology, growth, and yield, and on the dynamics and impact of its obligate major pest, the olive fruit fly and associated natural enemies. The thermal limits of olive and the fly differ and affect the trophic interactions crucial to estimating the bioeconomic impact of climate change in olive across the Mediterranean Basin.

Human-caused emissions of greenhouse gases are expected to rise carbon dioxide concentrations by as much as 57 % by 2050. Numerous agronomic publications affirm that rising carbon dioxide concentrations in the atmosphere maybe positive for agriculture because they increase the rate of photosynthesis and water use efficiency (Fuhrer 2003). These effects are strongest for plants with the C3 photosynthetic pathway, which include crops such as wheat, rice, and soybean, whose yields could increase by 30 % or more under a doubling of CO_2 concentrations. Carbon dioxide enrichment is also positive for C4 plants such as maize, millet, and sorghum, which exhibit a much smaller response (less than 10 % increase) (Hatfield et al. 2011). At the same time, there is a debate on whether expected increments in productivity due to CO_2 (CO_2 fertilization effect) have been overestimated, in light of the fact that projected increases in global atmospheric CO_2 are likely to change the biology of agricultural weeds, which in turn could significantly limit crop yields (Ziska and Dukes 2014).

In summary, evaluations by the Intergovernmental Panel on Climate Change (IPCC) indicate that the rise of CO_2 and associated “greenhouse” gases could lead to a 1.4 to 5.8 °C increase in global surface temperatures, with subsequent consequences on precipitation frequency and amounts. Temperature and water availability remain key factors in determining crop growth and productivity, so changes in these factors can lead to reduced crop yields. Climate-induced changes in insect pest, pathogen, and weed population dynamics and invasiveness could compound such effects. Increasing the frequency of crop loss due to these extreme events may overcome positive effects of moderate temperature and CO_2 increases. Increase in frequency and patterns of extreme weather events will affect the stability of as well as access to food supplies.

3 The vulnerability of agroecosystems

Today, monocultures have increased dramatically worldwide, mainly through the geographical expansion of land devoted to single crops and year-to-year production of the same crop species on the same land. No less than 80 % of the 1.5 billion hectares of arable land are devoted to monocultures of a few grains and animals. Wheat, corn, rice, and potatoes alone account for roughly 60 % of the world's vegetable food sources, and a mere 14 species of animals provide 90 % of all animal protein (Vigouroux 2011). Genetically, modern agriculture is shockingly dependent on a handful of varieties for its major crops. In the late twentieth century in the USA, 60–70 % of the total bean area was planted with 2–3 bean varieties, 72 % of the potato area with four varieties, and 53 % of the cotton area is planted with three varieties (Robinson and Wallace 1996). Available data indicates that today the amount of crop diversity per unit of arable land continues to decrease, partly explained by the increasing deployment of more about 175 million hectares of biotech crops (mainly soybean and maize) which were grown globally in 2013 and the rising tendency of growing large monocultures of maize, sugarcane, African palm, and soybeans for biofuels. In the past decade, more than 81 million acres of land worldwide have been sold to foreign investors through land deals (land grabs) and more than 60 % of crops grown on such lands in developing countries are monocultures intended for export. Two thirds of these agricultural land deals are in countries with serious hunger problems (Franco et al. 2014).

3.1 Early warnings

Many scientists have argued that the drastic narrowing of cultivated plant diversity has put world's food production in greater peril and have repeatedly warned about the extreme vulnerability associated with crop genetic uniformity, claiming that ecological homogeneity in agriculture is closely linked to pest invasions and outbreaks (Adams et al. 1971; Altieri and Nicholls 2004). These concerns are not new and became apparent in 1972 with the report Genetic Vulnerability of Major Crops (National Research Council 1972) which stated:

"Over the ages the tendency of crop improvement efforts has been to select varieties with traits that give the highest return, largely by concentrating on genetic strains that combine the most desirable traits. The resulting homogeneity and uniformity can offer substantial advantages in both the quantity and quality of crop harvested, but this same genetic homogeneity can also reflect greater susceptibility to pathogens. Thus it appears the more that agricultural selection disturbs the natural balance in favor of variety uniformity over large areas, the more vulnerable such varieties are to losses from epidemics." Paradoxically, the denudation of diversity by selective breeding has proven to be an undesirable side effect of scientific advancement.

This report was prepared by scientists who, alerted about the 1970's epidemic of southern corn leaf blight (*Helminthosporium maydis*) in the USA, became concerned about the potential for similar outbreaks in other major crops. The southern corn leaf blight epidemic in the USA resulted in a crop loss estimated to 15 % yield reduction in corn or in a loss of one billion dollars. The actual yield in 1970 was 45,439 hg/ha, considerably less than in 1969 (53,908 hg/ha) and in 1971 (55,297 hg/ha). With 23,211,600 ha sown in 1970, the projected production was 126, 289,673 t resulting in an actual shortfall of 20,818,673 t from expected. Estimating the calories (kcal) in 1 t of maize at 888, 889, the loss was equivalent to 18.5 trillion (18.5×1012) calories (Heinemann et al. 2013).

But there are other many other historical cases that prove that the drastic narrowing of cultivated plant diversity threatens world's food production (Altieri 1999a). The Irish Potato Famine resulted from the wide spread planting of genetically uniform clone (of a single variety called Lumpers) and the outbreak of the potato late blight (*Phytophthora infestans*) which caused 80% yield reduction. As a result, millions of Irish people starved to death and other two million emigrated. The great Bengal famine in India in 1943 was due to a devastating disease (*Cochliobolus miyabeanus*) that almost wiped out rice production. An excellent example of devastation of that scale by insect pests was encountered over a century ago in France when grapevine was totally wiped out by attacks on root stocks of *Phylloxera vertifoliae* until a resistant cultivar was introduced from the USA (Thrupp 1988). The substantial yield losses due to pests, about 20 to 30 % for most crops before harvest, despite the increase in the use of pesticides (about 4.7 billion pounds of pesticides were used worldwide in 1995, 1.2 billion pounds in the USA alone), is a clear indication that cultivated plants grown in genetically homogenous monocultures do not possess the necessary ecological defense mechanisms to prevent or tolerate the impact of pest outbreaks (Pimentel and Levitan 1986).

3.2 More monocultures-more vulnerability

One would think that all the above examples would warn the agricultural community about the risks associated with the homogenization of modern agroecosystems and that major shifts would have resulted towards increasing the ecological and genetic diversity foundations of major crops to reduce the risk of future outbreaks. Three decades later, the issue of agricultural vulnerability is still fresh, and debate continues on the risk that it poses now in the face of climate change. Many researchers are starting to realize that modern agricultural systems appear to be very vulnerable to variability in climate, whether naturally forced or due to human activities.

The worst drought in 50 years severely impacted crop production in the USA in 2012. The drought was estimated to have affected 26 of the 52 states and covered at least 55 % of the land area of the USA, which is almost 1 billion hectares. By the end of July 2012, compared with the average year, 38 % of the US maize crop had already been rated as poor and similarly 30 % of soybean was rated poor, due to drought and extreme heat. Given that the maize crop is the most important in the USA valued at US$76.5 billion in 2011, with a 30 % yield reduction, economic losses for 2012 were substantial (Heinemann et al. 2013). Since US maize and US soybean exports represent 53 and 43 % of global maize and soybean exports, respectively, the impact of the 2012 drought on international prices were significant. Increases of food prices of 3 to 4 % were experienced in 2013, with beef prices increasing by 4 to 5 %. In 2010, in Russia a severe drought led to the loss of one quarter of the country's wheat crop over 1 million hectares, with an estimated damage cost of US$1.4 billion. Heavy monsoon rains brought to 2011 Pakistan the worst flooding ever recorded, destroying 2.4 million hectares of cultivated land and killing 450,000 livestock animals at a cost of 2.9 billion dollars (IPCC 2014).

Large-scale changes in landscape diversity due to large plantations of agrofuels can lead to more insect outbreaks due to the expansion of monocultures at the expense of natural vegetation, directly affecting abundance and diversity of natural enemies of insect pests. In four US Midwest states, recent biofuel driven growth of monocultures resulted in lower landscape diversity, decreasing the supply of natural enemies to soybean fields and reducing biocontrol services by 24 %. This loss of biocontrol services cost soybean producers in these states an estimated $58 million per year in reduced yield and increased pesticide use (Landis et al. 2008).

Dealing with climate change will require strengthening the resilience of farmers and rural communities and to help them adapt to the impact of climate change. The key to developing appropriate and targeted adaptation efforts is to understand impact of climate change across different agroclimatic regions.

4 Traditional farming systems as models of resilience

Contrary to the monocultures of industrial agriculture, many traditional farming systems, which still persist in many developing countries, offer a wide array of management options and designs that enhance functional biodiversity in crop fields and, consequently, support the resilience of agroecosystems (Koohafkan and Altieri 2010; Toledo and Barrera-Bassols 2008). In continuously coping with extreme weather events and climatic variability through centuries, farmers living in harsh environments in Africa, Asia, and Latin America have developed and/or inherited complex farming systems managed in ingenious ways. These systems have allowed small farming families to meet their subsistence needs in the midst of environmental variability without depending on modern agricultural technologies (Denevan 1995). The continued existence of millions of hectares under traditional farming is a living proof of a successful indigenous agricultural strategy, which is a tribute to the "creativity" of small farmers throughout the developing world (Wilken 1987).

A manifestation of this creativity are the thousands of hectares of raised bed cultivation systems on seasonally flooded lands in savannas and in highland basins of Surinam, Venezuela, Colombia, Ecuador, Peru, and Bolivia. The origin and use of these systems have traditionally been associated with water management issues, either by providing opportunities to reduce the adverse impact of excess water on crop production, to actively harvest excess water or to irrigate crops in times of rainfall scarcity. Examples of farming in wetlands subjected to temporal flooding are the *chinampas* used in the Valley of Mexico (Armillas 1971), and the *waru warus* used near Lake Titicaca in Peru and Bolivia (Erickson and Chandler 1989).

Today, well into the first decade of the twenty-first century, millions of smallholders, family farmers, and indigenous people continue to practice resource-conserving farming. This is testament to the remarkable resilience of agroecosystems to continuous environmental and economic change, while contributing substantially to agrobiodiversity conservation and food security at local, regional, and national levels (Netting 1993). A review of 172 case studies and project reports from around the world shows that agricultural biodiversity as used by traditional farmers contributes to resilience through a number of, often combined, strategies: the protection and restoration of ecosystems, the sustainable use of soil and water resources, agroforestry, diversification of farming systems, various adjustments in cultivation practices, and the use of stress-tolerant crops and crop improvement (Mijatovic et al. 2013).

Despite the resilience of traditional agriculture, climate change poses serious challenges to about 370 million of the poorest farmers, who live in areas often located in arid or semiarid zones, and in ecologically vulnerable mountains and hills (Thornton 2003). In many countries, more and more people, particularly those at lower income levels, are now forced to live in marginal areas (i.e., floodplains, exposed hillsides, arid, or semiarid lands), where they are at risk from the negative impacts of climate variability. Even minor changes in climate can have disastrous impacts on the lives and livelihoods of these vulnerable groups. The implications for food security could be very profound, especially for subsistence farmers living in remote and fragile environments that are expected to produce very low yields. These farmers depend on crops that could be dramatically affected, such as maize, beans, potatoes, and rice.

Despite the serious implications of model predictions, these data represents a broad brush approximation of the effects of climate change on small-scale agriculture; in many cases, ignoring the adaptive capacity of small farmers who use several agroecological strategies and socially mediated solidarity networks to cope with and even prepare for extreme climatic variability (Altieri and Koohafkan 2008). Many researchers have found that despite their high-exposure sensitivity, indigenous peoples and local communities are actively responding to changing climatic conditions and have demonstrated their resourcefulness and resilience in the face of climate change. Strategies such as maintaining genetic and species diversity in fields and herds provide a low-risk buffer in uncertain weather environments (Altieri and Nicholls 2013). By creating diversity temporally as well as spatially, traditional farmers add even a greater functional diversity and resilience to systems with sensitivity to temporal fluctuations in climate (Perfecto et al. 2009).

A multi-country study that explored resilience of African smallholder farming systems to climate variability and change between 2007 and 2010, revealed farmers' priorities for strategies to adapt to climate change: (a) improving soil fertility with green manures and organic residues, (b) conserving water and soil, (c) developing mechanisms for establishment and sustenance of local strategic food reserves, (d) supporting traditional social safety nets to safeguard vulnerable social groups, (e) conserving indigenous fruit trees and other locally adapted crop varieties,(f) using alternative fallow and tillage practices to address climate change-related moisture and nutrient deficiencies, and (g) changing land topography to address the moisture deficiencies associated with climate change and reduce the risk of farm land degradation (Mapfumo et al. 2013).

Whether recognized or not by the scientific community, this ancestral knowledge constitutes the foundation for actual and future agricultural innovations and technologies. For years, agroecologists have argued that the new models of agriculture that humanity will need in the immediate future should be rooted in the ecological rationale of traditional small-scale agriculture, which represents long-established, successful, and adaptive forms of agriculture (Altieri 2004). Given the resilience of diversified small farming systems, understanding the agroecological features of traditional agroecosystems is an urgent matter, as they can serve as the foundation for the design of agricultural systems that are resilient to climate change (Swiderska 2011).

5 The ecological role of biodiversity in agroecosystems

In agricultural systems, the level of existing biodiversity can make the difference between the system being stressed or resilient when confronting a biotic or abiotic perturbation. In all agroecosystems, a diversity of organisms is required for ecosystem function and to provide environmental services (Altieri and Nicholls 2004). When agroecosystems are simplified, whole functional groups of species are removed shifting the balance of the system from a desired to a less desired state, affecting their capacity to respond to changes and to generate ecosystem services (Folke 2006). Two categories of diversity can be distinguished in agroecosytems: functional and response diversity. Functional diversity refers to the variety of organisms and the ecosystem services they provide for the system to continue performing (Loreau et al. 2001). Response diversity is the diversity of responses to environmental change among species that contribute to the same ecosystem function. An agroecosystem that contains a high degree of response diversity will be more resilient against various types and degrees of shocks (Cabell and Oelofse 2012).

Biodiversity enhances ecosystem function because different species or genotypes perform slightly different functions and therefore have different niches (Vandermeer et al. 1998). In general, there are many more species than there are functions and thus redundancy is built into the agroecosystem. Therefore, biodiversity enhances ecosystem function because those components that appear redundant at one point in time 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 ecosystem services. On the other hand, a diversity of species acts as a buffer against failure due to environmental fluctuations, by enhancing the compensation capacity of the agroecosystem, because if one species fails, others can play their role, thus leading to more predictable aggregate community responses or ecosystem properties (Lin 2011).

6 Enhancing agrobiodiversity to reduce vulnerability

For decades, agroecologists have contended that a key strategy in designing a sustainable agriculture is to reincorporate diversity into the agricultural fields and surrounding landscapes and manage it more effectively (Altieri and Nicholls 2004). Diversification occurs in many forms: genetic variety and species diversity such as in variety mixtures and polycultures, and over different scales within field and landscape level as in the case of agroforestry, crop-livestock integration, hedgerows, corridors, etc., giving farmers a wide variety of options and combinations for the implementation of this strategy. Emergent ecological properties develop in diversified agroecosystems that allow the system to function in ways that maintain soil fertility, crop production, and pest regulation. There are many agroecological management practices that increase agroecosystem diversity and complexity as the foundation for soil quality, plant health, and crop productivity. It is generally believed by many entomologists and plant pathologists that inter-specific (species) and intra-specific (genetic) diversity reduces crop vulnerability to specific diseases and insect pests. There is a vast body of literature documenting that in diverse cropping systems (variety mixtures, polycultures, agroforestry systems, etc.), there is less insect pest incidence and the slowing down of the rate of disease development, leading to less crop damage and higher yields in mixed crops as compared to the corresponding monocultures (Francis 1986; Altieri 2002).

Swiderska (2011) found that maintenance of diverse traditional crop varieties (maize, potatoes, rice) and access to seeds was essential for adaptation and survival by poor farmers in China, Bolivia, and Kenya. Even when planted alongside modern crops, traditional crop varieties are still conserved, providing a contingency when conditions are not favorable (Fig. 3). For example in China, when farmers from 15 different townships grew four different mixtures of rice varieties over 3000 ha, suffered 44 % less blast incidence, and exhibited 89 % greater yield than homogeneous fields without the need to use fungicides (Zhu et al. 2000). Maintaining species diversity in fields acts as a buffer against insect pests and also against uncertain weather. In Kenya, scientists at the International Center of Insect Physiology and Ecology (ICIPE) developed a push-pull system which uses two kinds of crops that are planted together with maize: a plant that repels these borers (the push) and another that attracts (the pull) them (Kahn et al. 1998). Two of the most useful trap crops that pull in the borers' natural enemies such as the parasitic wasp (*Cotesia sesamiae*) are Napier grass and Sudan grass, both important fodder plants; these are planted in a border around the maize. Two excellent borer-repelling crops, which are planted between the rows of maize, are molasses grass, which also repels ticks, and the leguminous silverleaf (*Desmodium*), which in addition can suppress the parasitic weed *Striga* by a factor of 40 compared to maize monocrop. *Desmodium's* N-fixing ability increases soil fertility leading to a 15–20 % increase in maize yield. It is also an excellent forage (Kahn et al. 1998).

Given the positive role of biodiversity in providing stability to agroecoystems, many researchers have argued that enhancing crop diversity will be even more important in a future exhibiting dramatic climatic swings. Greater agroecosystem diversity may buffer against shifting rainfall and temperature patterns and possibly reverse downward trends in yields over the long term as a variety of crops and varieties respond differently to such shocks (Altieri and Koohafkan 2013).

6.1 Plant diversity and resiliency

Diversified farming systems such as agroforestry, silvopastoral, and polycultural systems provide a variety of examples on how complex agroecosystems are able to adapt and resist the effects of climate change. Agroforestry systems are examples of agricultural systems with high structural complexity that have been shown to buffer crops from large fluctuations in temperature (Lin 2011), thereby keeping the crop closer to its optimum conditions. More shaded coffee systems have shown to protect

Fig. 3 Maintenance and deployment of traditional varieties managed with traditional technologies buffers against climatic risk. Many farmers in the Mixteca Alta of Mexico still use the maiz de cajete which is more resistant to drought events than maiz de temporal. This maize is planted at a certain soil depth that exhibits enough moisture for the maize to emerge without rainfall and produce reasonable subsistence yields (Rogé et al. 2014)

crops from decreasing precipitation and reduced soil water availability because the over story tree cover is able to reduce soil evaporation and increase soil water infiltration (Lin 2007).

Intercropping enables farmers to produce various crops simultaneously and minimize risk (Vandermeer 1989). Polycultures exhibit greater yield stability and less productivity declines during a drought than in the case of monocultures. Natarajan and Willey (1996) examined the effect of drought on enhanced yields with polycultures by manipulating water stress on intercrops of sorghum and peanut, millet and peanut, and sorghum and millet. All the intercrops over yielded consistently at five levels of moisture availability, ranging from 297 to 584 mm of water applied over the cropping season. Quite interestingly, the rate of over yielding actually increased with water stress, such that the relative differences in productivity between monocultures and polycultures became more accentuated as stress increased (Natarajan and Willey 1996).

Intensive silvopastoral systems (ISS) are a sustainable form of agroforestry for livestock production that combines fodder shrubs planted at high-densities trees and palms and improves pastures. High stocking and the natural production of milk and meat in these systems are achieved through rotational grazing with electric fencing and a permanent supply of water for the cattle. At the El Hatico farm in the Valle del Cauca, Colombia, a five-story ISS composed of a layer of grasses, *Leucaena* shrubs, medium-sized trees, and a canopy of large trees have over the last 18 years allowed to increase stocking rates to 4.3 dairy cows ha−1 and milk production by 130 %, and to completely eliminate the use of chemical fertilizers. 2009 was the driest year in El Hatico's 40-year record, with precipitation having dropped by 44 % compared to the historical average. Despite a reduction of 25 % in pasture biomass, the fodder production of trees and shrubs remained constant throughout the year, neutralizing the negative effects of drought on the whole system. In response to the extreme weather, the farm had to adjust its stocking rates and increase energy supplementation. In spite of this, the farm's milk production for 2009 was the highest on record with a surprising 10 % increase compared to the previous 4 years. Meanwhile, farmers in other parts of the country reported severe animal weight loss and high mortality rates due to starvation and thirst (Fig. 4). The productive performance of El Hatico during the exceptionally hot and dry period of El Nino Southern Oscillation illustrates the huge potential of SPS as a sustainable intensification strategy for climate change adaptation and mitigation (Murgueitio et al. 2011). The combined benefits of water regulation, favorable microclimate, biodiversity, and carbon stocks in the above-described diversified farming systems not only provide environmental goods and services for producers but also a greater resilience to climate change.

6.2 Restoring diversity in large-scale monocultures

Although contemporary notions of modern mechanized farming connote the necessity of monocultures, appropriate technology could be developed to mechanize large-scale multiple cropping systems (Horwith 1985). Simpler diversification schemes based on 2–3 plant species may be more amenable for large-scale farmers and can be managed using modern equipment (Machado 2009). One of such schemes is strip intercropping, which consists in the production of more than one crop in strips that are narrow enough for the crops to interact, yet wide enough to permit independent cultivation. Agronomically, beneficial strip intercropping systems have usually included corn or sorghum, which readily respond to

Fig. 4 Highly productive pastures in the tropics require water and nitrogen; therefore, they are highly vulnerable to droughts as shown in this example from the Llanos Orientales in Colombia (*left photo*). In contrast, intensive silvopastoral systems with an overstory of shrubs and trees are resilient allowing for continual fodder availability for cows which maintain stable levels of milk production despite low rainfall (*right photo*)

higher light intensities. Studies with corn and soybean strips four to 12 rows wide have demonstrated increased corn yields (+5 to+26 %) and decreased soybean yields (−8.5 to −33 %), as strips get narrower. Alternating corn and alfalfa strips provided greater gross returns than sole crops. Twenty-feet wide strips were most advantageous, with substantial economic returns over the sole crops (West and Griffith 1992). This advantage is critical to farmers that have debt-to-asset ratios of 40 % or higher ($40 debt for every $100 of assets). Such a level has already been reached by more than 11–16 % of the US Midwest farmers who desperately need to cut on costs of production by adopting diversification strategies (Francis et al. 1986).

No-till row crop production is also promising given its soil conservation effects and moisture improvement potential. Although these systems are highly dependent on herbicides, there are some organic farmers who practice it without synthetic herbicides. A breakthrough occurred with the discovery that certain winter annual cover crops, notably cereal rye and hairy vetch, can be killed by mowing with an innovative no-till roller/crimper at a sufficiently late stage in their development and cut close to the ground. These plants generally do not regrow significantly, and the clippings form an in situ mulch through which vegetables can be transplanted with no or minimal tillage. The mulch hinders weed seed germination and seedling emergence, often for several weeks. As they decompose, many cover crop residues can release allelopathic compounds that may suppress the weed growth (Moyer 2010). This inhibition is caused by phytotoxic (allelopathic) substances that are passively liberated through decomposition of plant residues. There is a long list of green manure species that have phytotoxic effects. This effect is usually sufficient to delay the onset of weed growth until after the crop's minimum weed-free period, which makes post-plant cultivation, herbicides, or hand weeding unnecessary, yet exhibiting acceptable crop yields. Tomato and some late-spring brassica plantings perform especially well, and some large-seeded crops such as maize and beans can be successfully direct-sown into cover crop residues. Not only can cover crops planted in no-till fields fix nitrogen in the short term, they can also reduce soil erosion and mitigate the effects of drought in the long term, as the mulch conserves soil moisture. Cover crops build vertical soil structure as they promote deep macropores in the soil, which allow more water to penetrate during the winter months and thus improve soil water storage (Altieri et al. 2011).

6.3 Performance of biodiverse agroecosystems under extreme climatic events

A survey conducted in Central American hillsides after Hurricane Mitch showed that farmers using diversification practices such as cover crops, intercropping, and agroforestry suffered less damage than their conventional monoculture neighbors (Fig. 5). The survey, spearheaded by the *Campesino a Campesino* movement, mobilized 100 farmer-technician teams to carry out paired observations of specific agroecological indicators on 1804 neighboring sustainable and conventional farms. The study spanned 360 communities and 24 departments in Nicaragua, Honduras, and Guatemala. It was found that sustainable plots had 20 to 40 % more topsoil, greater soil moisture and less erosion and experienced lower economic losses than their conventional neighbors (Holt-Giménez 2002). Similarly in Sotonusco, Chiapas, coffee systems exhibiting high levels of vegetational complexity and plant diversity suffered less damage from Hurricane Stan than more simplified coffee systems (Philpott et al. 2009). Forty days after Hurricane Ike hit Cuba in 2008, researchers conducted a farm survey in the Provinces of Holguin and Las Tunas and found that diversified farms exhibited losses of 50 % compared to 90 or 100 % in neighboring monocultures (Fig. 6). Likewise, agroecologically managed farms showed a faster productive recovery (80–90 % 40 days after the hurricane) than monoculture farms (Rosset et al. 2011).

Fig. 5 After Hurricane Mitch in Central America, Honduran farms under monoculture exhibited higher levels of damage in the form of mudslides (*top photo*) than neighboring biodiverse farms featuring agroforestry systems, contour farming, cover crops, etc. (*bottom photo*)

All the above studies emphasize the importance of enhancing plant diversity and complexity in farming systems to reduce vulnerability to extreme climatic events. The above observations have bolstered a new recognition that biodiversity is integral to the maintenance of ecosystem functioning and points to the utility of crop diversification strategies used by traditional farmers as an important resilience strategy for agroecosystems (Altieri and Nicholls 2013).

Fig. 6 A diversified farm in Sancti-Spiritu, Cuba, exhibiting crop-pasture rotations and a complex matrix of multiple purpose windbreaks and hedgerows that protect against the effects of hurricanes

7 Soil management and resiliency

7.1 Enhancing soil organic matter

Many traditional and organic farmers add large quantities of organic materials on a regular basis via animal manures, composts, tree leaves, cover crops, and rotation crops that leave large amounts of residue, etc., as a key strategy used to enhance soil quality. Soil organic matter (SOM) and its management are at the heart of creating healthy soils with an active biological activity and good physical and chemical characteristics. Of utmost importance for resiliency is that SOM improves the soil's water retention capacity enhancing the drought tolerance by crops and improves infiltration-diminishing runoff avoiding that soil particles will be transported with water under intense rains. SOM also improves surface soil aggregation holding tightly the soil particles during rain or windstorms. Stable soil aggregates resist movement by wind or water (Magdoff and Weil 2004).

Organically rich soils usually contain symbiotic mycorrhizal fungi, such as arbuscular mycorrhizal (AM) fungi, which form a key component of the microbial populations influencing plant growth and soil productivity. AM fungi are important in sustainable agriculture because they improve plant water relations and thus increase the drought resistance of host plants (Garg and Chandel 2010). The abilities of specific fungus-plant associations to tolerate drought are of great interest in areas affected by water deficits as AM fungi infection have been reported to increase nutrient uptake in water-stressed plants and to enable plants to use water more efficiently and to increase root hydraulic conductivity.

Crop productivity under dry land conditions is largely limited by soil water availability. SOM content (% SOM) is a reliable index of crop productivity in semiarid regions because SOM aids growth of crops by improving the soil's ability to store and transmit air and water and thus enhance drought resistance. In a study of the semiarid Pampas of Argentina, researchers found that wheat yields were related to both soil water retention and total organic C contents in the top layers (0–20 cm) in years with low moisture availability. Dependence of wheat yields on soil water retention and on TOC contents under water deficit was related to the positive effect of these soil components on plant-available water. Losses of 1 Mg SOM per hectare were associated with a decrease in wheat yield of approximately 40 kg/ha. These results demonstrate the importance of using cultural practices that enhance SOM and thus minimize losses of soil organic C in semiarid environments (Diaz-Zorita et al. 1999).

In what is the longest running, side-by-side comparison of organic and chemical agriculture in the USA, researchers have compared since 1981 the performance of corn and soybean during the transition from chemical to organic agriculture (Rodale Institute 2012). They found that organic corn yields were 31 % higher than conventional in years of drought. These drought yields are remarkable when compared to genetically engineered "drought tolerant" varieties, which saw increases of only 6.7 to 13.3 % over conventional (non-drought resistant) varieties (Fig. 7).

7.2 Managing soil cover

Protecting the soil from erosion, drying up, and improving soil moisture levels and water circulation is also a fundamental

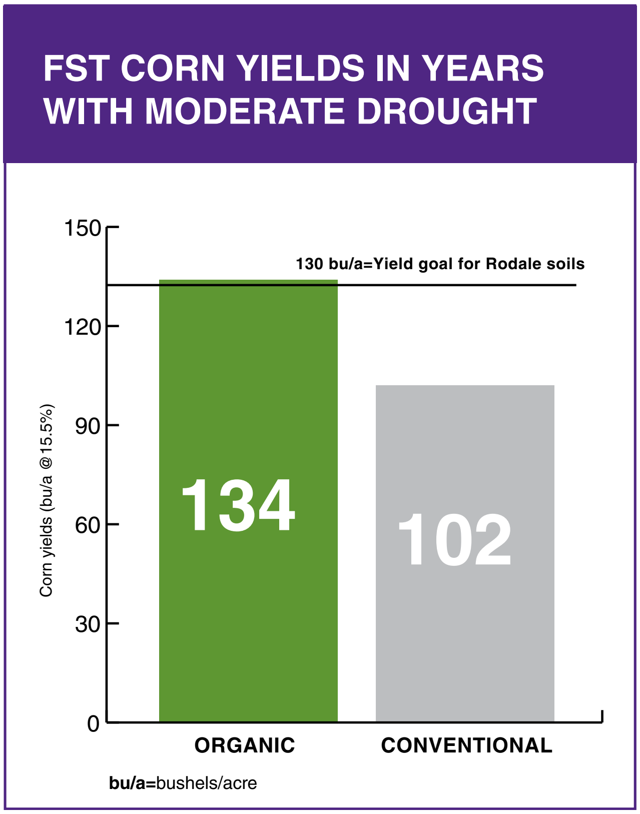

Fig. 7 Yields of organic maize compared to conventional in years under drought in PA, USA (Rodale Institute 2012)

strategy to enhance the resiliency of agroecosystems. Cover crop mulching and green manures offer great agroecological potential as such practices conserve soil, improves the soil ecology, stabilizes and enhances crop yield and water conservation. Stubble mulching disrupts the soil drying process by protecting the soil surface with residues. Mulching reduces the wind speed by up to 99 % and, therefore, losses due to evaporation are significantly reduced. In addition, cover crop and weed residues can improve water penetration and decrease water runoff losses by 2 to 6 fold. The *frijol tapado* or covered bean system is an ancient slash/mulch system common in the hillsides of Central America (Buckles et al. 1998). This system of migratory agriculture, allows 3–5 months of bean production in 1 year, taking advantage of the high precipitation and the residual moisture maintained by the slash/mulch after the rains. *Frijol tapado* management consists of first selecting appropriate land and then slashing paths through the vegetation to create access for subsequent planting, broadcasting at high rates (25 to 40 kg of seed per hectare) and slashing of fallow vegetation over the bean seeds. *Frijol tapado* is usually grown on hill sides, preferably facing the morning sun so that leaves and pods of the bean plants dry quickly in the morning (they are susceptible to rot diseases) and the plants receive maximum sunlight, since mornings are often sunny and rain usually falls in the afternoon. Farmers look for land with a cover of tall herbs or low shrubs; there must be enough plant material to provide a mulch which can completely cover the soil. Areas dominated by grasses are avoided since they regrow quickly and compete strongly with the beans. The fields are then left untouched until harvest. Typically, the mulch is not too thick as to result in low bean germination and survival, and therefore low yields, while maintaining soil moisture and protecting the soil against erosion. The absence of burning and cultivation and the presence of thick mulch prevent the germination and growth of weeds. The fallow period reduces the pathogens in the soil, and the mulch protects the bean plants from soil particle splash during rains. The system is adapted to fragile slope ecosystems. The soil is not disturbed by cultivation and the mulch protects it from erosion. Moreover, the natural root system is left intact and the vegetation's fast regrowth further reduces the risk of erosion and restores soil fertility (Buckles et al. 1998).

In an effort to emulate and improve the *frijol tapado* system, throughout Central America, several non-government organizations have promoted the use of grain legumes to be used as green manure, an inexpensive source of organic fertilizer to build up organic matter (Altieri 1999b). Hundreds of farmers in the northern coast of Honduras are using velvet bean (*Mucuna pruriens*) with excellent results, including corn yields of about 3000 kg/ha, more than double the national average, erosion control, weed suppression, and reduced land preparation costs. The velvet beans produce nearly 30 t/ha of biomass per year, or about 90–100 kgN/ha/year (Flores 1989). The system diminishes drought stress, because the mulch layer left by *Mucuna* helps conserve water in the soil profile, making nutrients readily available in synchrony with periods of major crop uptake (Bunch 1990).

Taking advantage of well-established farmer-to-farmer networks such as the *Campesino a Campesino* movement in Nicaragua and elsewhere, the spread of this simple technology has occurred rapidly. In just 1 year, more than 1000 peasants recovered degraded land in the Nicaraguan San Juan watershed (Holt-Gimenez 1996). In Cantarranas, Honduras, there was massive adoption of velvet bean which triple maize yields to 2500 kg/ha while labor requirements for weeding were cut by 75 %. In Central America and Mexico, an estimated 200, 000 farmers are using some 14 different species of green manure and cover crops (Bunch 1990).

Today, well over 125,000 farmers are using green manure and cover crops in Santa Catarina, Brazil. Hillside family farmers modified the conventional no-till system by initially leaving plant residues on the soil surface and first noticing reductions in soil erosion and lower fluctuations in soil moisture and temperature and, later, that repeated applications of fresh biomass improved soil quality, minimized erosion and weed growth, and improved crop performance (Fig. 8). These novel systems rely on mixtures for both summer and winter cover cropping which leave a thick residue mulch layer on which after the cover crops are rolled, traditional grain crops

Fig. 8 In Santa Catarina, southern Brazil, family farmers developed an organic no-till system which does not rely on herbicides. By flattening cover crop mixtures on the soil surface as a strategy to reduce soil erosion and lower fluctuations in soil moisture and temperature, these farmers improve soil quality enhancing weed suppression and crop performance (Altieri et al. 2011)

(corn, beans, wheat, onions, tomatoes, etc.) are directly sowed or planted, suffering very little weed interference during the growing season and reaching agronomically acceptable yield levels (Altieri et al. 2011). During the 2008–2009 agricultural cycle, which experienced a severe drought, conventional maize producers exhibited an average yield loss of 50 %, reaching productivity levels of 4500 kg/ha. However, the producers who had switched to no-till agroecological practices experienced smaller losses, around 20 %, confirming the greater resilience of these systems compared to those using agrochemicals (Petersen et al. 1999).

7.3 Water harvesting

In many parts of the world, such as in sub-Saharan Africa, 40 % of the farmland is located in semiarid and dry sub-humid savannahs increasingly subjected to frequent occurrence of water scarcity. However, in most years, there is more than enough water to potentially produce crops. The problem is that rainfall is concentrated in 2–3 months of the year and/or large volumes of water are lost through surface runoff, soil evaporation, and deep percolation. The challenge is how to capture that water, store it in the soil and make it available to crops during times of scarcity. A variety of rainwater harvesting and floodwater harvesting techniques have been recorded in much of the developing world (Reij et al. 1996; Barrow 1999).

An old water harvesting system known as *zai* is being revived in Mali and Burkina Faso. The *zai* are pits that farmers dig in often rock-hard barren land, into which water otherwise could not penetrate. The pits are typically between 10–15 cm deep and 20–30 cm in diameter and are filled with organic matter (Zougmoré et al. 2004). The application of manure in the pits further enhances growing conditions, and simultaneously attracts soil-improving termites, which dig channels and thus improve soil structure so that more water can infiltrate and held in the soil. By digesting the organic matter, the termites make nutrients more easily available to plants. In most cases, farmers grow millet or sorghum or both in the *zai*. At times the farmers sow trees directly together with the cereals in the same *zai*. At harvest, farmers cut the stalks off at a height of about 50–75 cm, which protect the young trees from grazing animals. Farmers use anywhere from 9000 to 18,000 pits per hectare, with compost applications ranging from 5.6 to 11 t/ha (Critchley et al. 2004).

Over the years, thousands of farmers in the Yatenga region of Burkina Faso have used this locally improved technique to reclaim hundreds of hectares of degraded lands. Farmers have become increasingly interested in the *zai* as they observe that the pits efficiently collect and concentrate runoff water and function with small quantities of manure and compost. The use of *zai* allows farmers to expand their resource base and to increase household security (Reij 1991). Yields obtained on fields managed with *zai* are consistently higher (ranging from 870 to 1590 kg/ha) than those obtained on fields without *zai* (average 500–800 kg/ha).

In Niger, traditional planting pits were improved by making them into water-collecting reservoirs imitating part of a soil improvement technology traditionally used in other parts of the country and in Burkina Faso. From Burkina Faso, it has most recently been reported that villages that adopted land reclamation techniques such as this pitting through crusted soils, filling the pits with manure and water, have seen crop yields rise by 60 %, while villages that did not adopt these techniques realized much smaller gains in crop yields under very recent rainfall increases (Critchley 1989). In north Nigeria, small pits in sandy soil are filled with manure for keeping transplanted tree seedlings wet after the first rains.

In summary the literature suggests that agroecosystems will be more resilient when inserted in a complex landscape

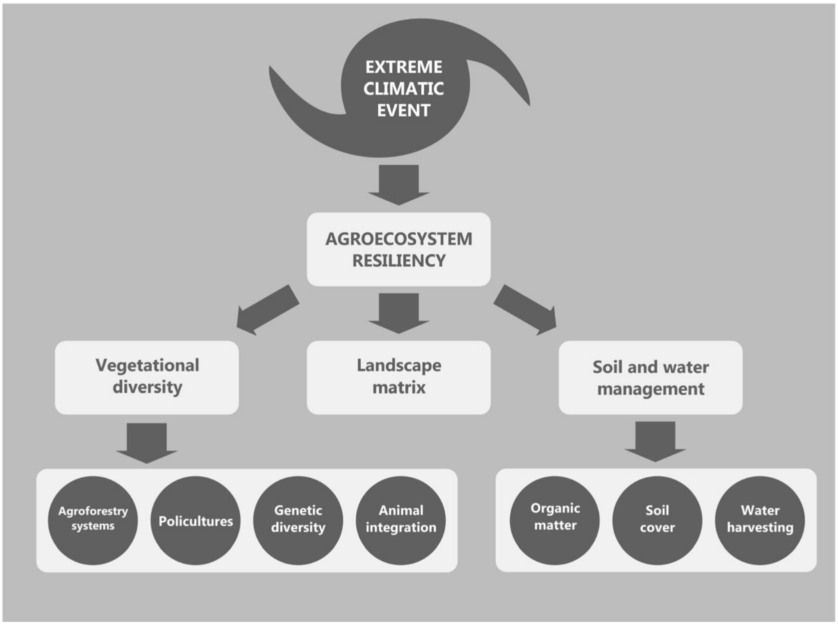

Fig. 9 Landscape, on-farm diversity, and soil and water features that enhance the ecological resilience to extreme climatic events (Altieri and Koohafkan 2013)

matrix, featuring genetically heterogeneous and diversified cropping systems managed with organic matter rich soils and water conservation techniques (Fig. 9) Many of the 60 case studies of sustainability assessments conducted in Latin America using the MESMIS framework have confirmed this (Astier et al. 2012).

8 A conceptual framework to assess the resiliency of farming systems

Resilience is defined as the ability of a social or ecological system to absorb disturbances while retaining its organizational structure and productivity, the capacity for self-organization, and the ability to adapt to stress and change following a perturbation (Cabell and Oelofse 2012). Resilience is a product of the dynamics of a social-ecological system, whose constituent parts are integrated and interdependent (Adger 2000). Resilience can be understood as the propensity of a system to retain its organizational structure and productivity following a perturbation. Thus, a "resilient" agroecosystem would be capable of providing food production, when challenged by severe drought or by excess rainfall. Conversely, vulnerability can be defined as the possibility of loss of biodiversity, soil, water, or productivity by an agroecosystem when confronted with an external perturbation or shock. Vulnerability refers to the degree to which a system is susceptible to, and unable to cope with, adverse effects of climate variability and extremes and denotes a state of susceptibility to harm from exposure to stresses associated with environmental change and from the absence of capacity to adapt (Folke 2006).

Thus, the resulting risk is the product between threat, vulnerability, and response capacity as described in the following equation (Nicholls and Altieri 2013):

$$\text{Risk} = \frac{\text{Vulnerability*Threat}}{\text{Response Capacity}}$$

Risk	is understood as any natural phenomena (drought, hurricane, flood, etc.) that signifies a change in the environment inhabited by a rural community.
Vulnerability	is determined by biophysical features of the farm and socio-economic conditions of the farmers that enhance or reduce the exposure to the threat.
Threat	is the climatic event's intensity, frequency, duration, and level of impact (i.e., yield losses due to storm or drought).
Response capacity	is the ability (or lack of) of the farming systems and the farmers to resist and recover from the threat depending on the level of social organization and the agroecological features (i.e., crop diversity) of the farms.

In summary, for an event to be considered a risk depends on whether in a particular region there is a community that is vulnerable to it. In order for the event to become a threat, there should be a high probability that will occur in that region, and for the threat to be devastating will depend on the magnitude of the event and the level of vulnerability of the community. Such vulnerability can be reduced by the "response capacity" defined as the agroecological features of the farms and the

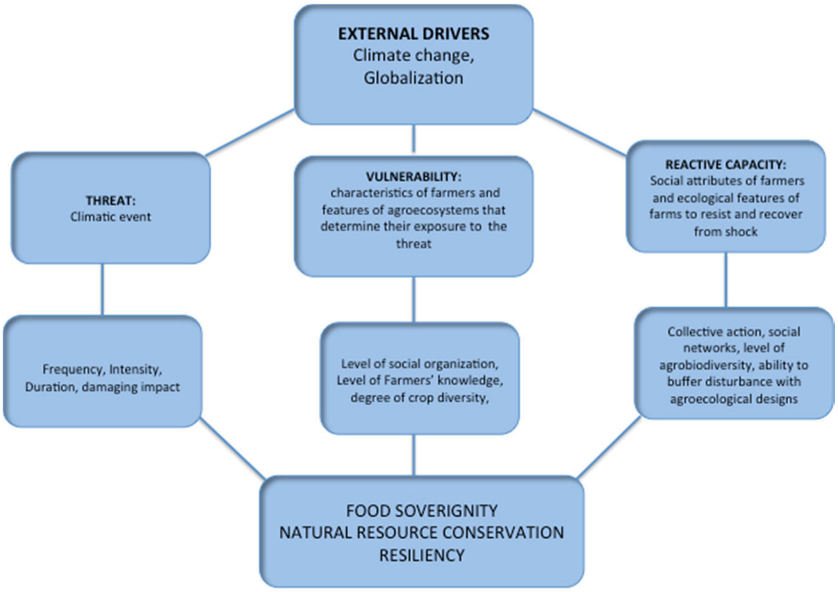

Fig. 10 Socio-ecological features that determine the vulnerability and reactive capacity of farmers to enhance the resiliency of their systems and communities (Nicholls et al. 2013)

management strategies used by farmers to reduce climatic risks and to resist and recover from such events. Therefore, adaptation refers to the adjustments made by farmers to reduce risks. The capacity of farmers to adapt is based on the individual or collective reserves of human and social capital that include attributes such as traditional knowledge and skills, levels of social organization, and safety networks, etc. As observed in Fig. 10, the level of vulnerability of a farm is determined by its type of agroecological infrastructure (level of landscape, crop and genetic diversity, soil quality and cover, etc.) and social traits of the family or community (levels of organization and networking, food self-sufficiency, etc.). The vulnerability can be reduced by the capacity of response of the farmers and their farms, which in turn determine their ability to resist events and recover function and infrastructure.

9 Methodological attempts to assess resiliency

In 2011, a group of Latin American agroecologists associated to REDAGRES: "Red IberoAmericana para el Desarrollo de Sistemas Agricolas Resilientes al Cambio Climatico—www.redagres.org" engaged in a 1-year survey of small farming systems in selected regions of seven countries in order to identify systems that have withstood climatic events recently or in the past and understand the agroecological features of such systems that allowed them to resist and/or recover from droughts, storms, floods, or hurricanes. Identified principles and mechanisms that underlie resiliency were then transmitted to other farmers in the region via field days where farmers can visit the resilient farms and discuss among themselves the features of such farms and how to replicate them in other farms. Cross-visits were also organized where resilient farmers can visit other communities in other regions and share their experiences, management systems, and socio-ecological resiliency strategies. Researchers and a group of selected farmers elaborated a manual containing two main sections: (a) a simple methodology with indicators that will allow farmers to assess whether their farms can withstand a major climatic event (drought or hurricane) and what to do to enhance the resiliency of the farm and (b) a description of the main socio-ecological principles and practices that farming families can use individually or collectively (at the community level) to enhance the adaptability of the farming systems to climate change (Nicholls et al. 2013).

Using the conceptual resiliency framework described above, the teams engaged in socio-ecological research in the selected farming systems in each country and developed a methodology to understand the agroecological features of the farming systems and the social strategies used by farmers that allowed them to resist and/or recover from droughts, storms, floods, or hurricanes (Nicholls and Altieri 2013). To illustrate the application of the methodologies, data is presented from two case studies conducted in: (a) Carmen del Viboral, Antioquia, Colombia, and (b) Mixteca Alta, Oaxaca, Mexico.

9.1 Carmen del Viboral

In this study, researchers assessed the resiliency of six farms (three conventionally managed with agrochemicals and without soil conservation practices and three agroecological diversified farms with soil conservation practices) exhibiting similar slope and exposure conditions (Henao 2013).

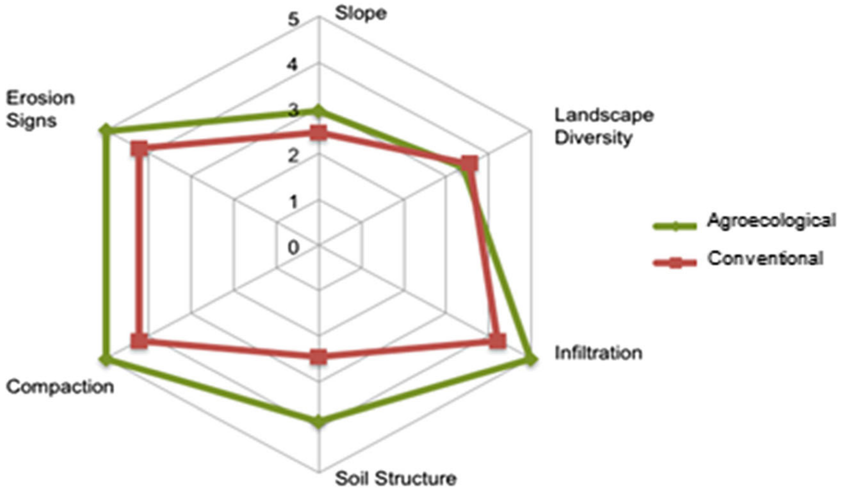

Fig. 11 An amoeba diagram showing vulnerability values of conventional (*red*) versus agroecological (*green*) farms in Antioquia, Colombia (Henao 2013)

The team developed six indicators to estimate vulnerability (slope, landscape diversity, soil's susceptibility to erosion) and capacity of response (soil conservation practices, water management practices, crop diversity levels, food self-sufficiency, etc.) estimated on the three agroecological farms and the three conventional farms. By actually giving values (from 1 to 5, values close to 1 or 2 express a higher level of vulnerability) to these indicators, it was possible to compare the farms in an amoeba diagram (Fig. 11). Clearly, the agroecological farms (green) were less vulnerable than the conventional ones (red). The team also applied 13 indicators to assess the capacity of response exhibited by the farmers, and clearly again the agroecological farms (green) exhibited higher response capacity than the conventional ones (red) (Fig. 12). Applying the methodology and placing the risk values in a triangle, it was clear that the agroecological farms (green dots in Fig. 13) exhibited low vulnerability due to their high response capacity in relation to the conventional farms (orange dots in Fig. 13), which exhibited higher vulnerability and a lower response capacity.

9.2 Mixteca Alta

This study conducted in Oaxaca, Mexico, describes how small farmers adapted to and prepared for past climate challenges, and also what are they doing to deal with recent increases in temperature and rainfall intensity, and later rainfall onset (Rogé et al. 2014). Farmers identified 14 indicators to evaluate the adaptive capacity of four agroecosystems located in Zaragoza and El Rosario communities using the form described in Table 1. Researchers pooled the agroecosystem evaluations within each community by assigning numerical scores of 0 for marginal, 1 for acceptable, and 2 for optimal. Farmers analyzed outcomes by drawing bar plots of the pooled scores for their community.

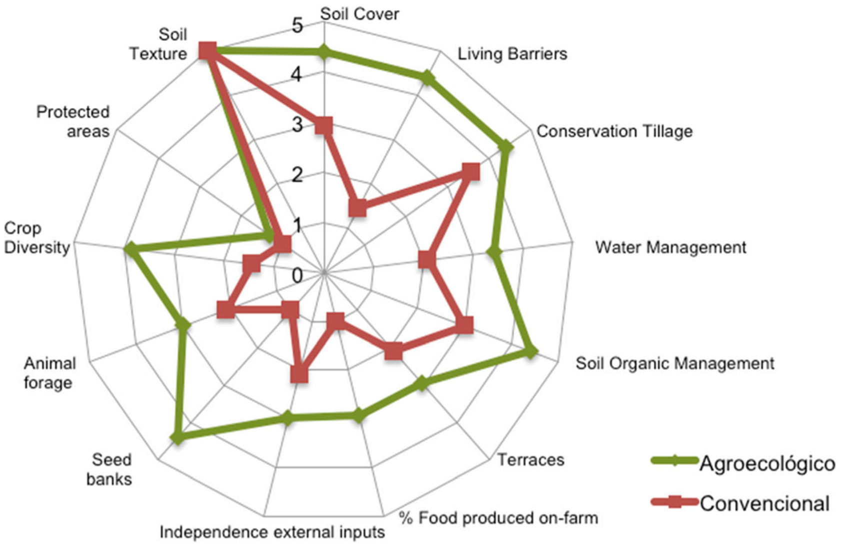

Fig. 12 An amoeba diagram depicting values of capacity of response of farmers managing conventional (*red*) versus agroecological (*green*) farms in Antioquia, Colombia (Henao 2013)

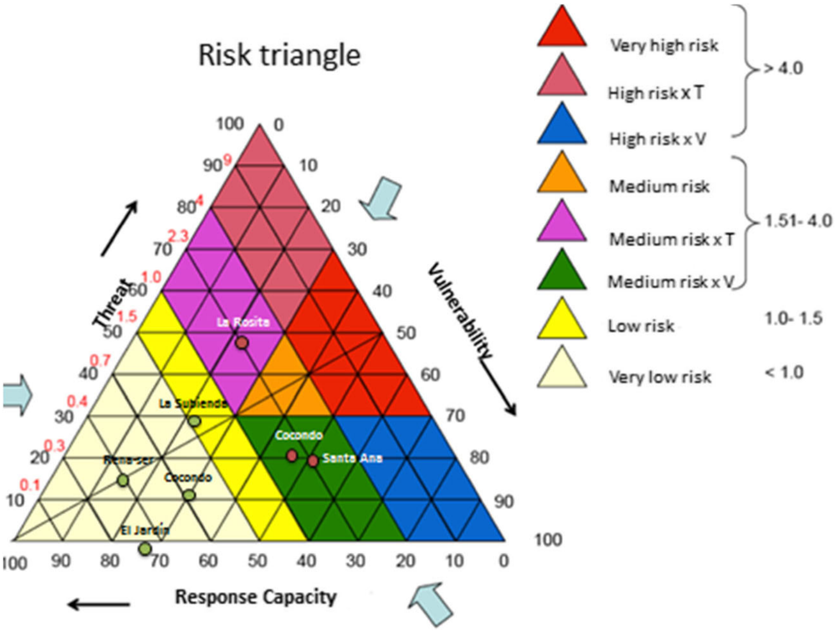

Fig. 13 A risk triangle showing the location of agroecological (*green dots*) and conventional (*orange dots*) farms in Antioquia along a gradient of vulnerability and capacity of response values (Henao 2013)

Farmers were prompted to analyze the results of their evaluations as a group by addressing the following questions:

- How to obtain more happy faces (i.e., the optimal condition) in the landscape, farmer management, and soil quality categories?
- How to maintain the happy faces (i.e., optimal condition) that you already have in the landscape, farmer management, and soil quality categories?

Table 1 Forms used by farmers to evaluate four agroecosystems in each community of Zaragoza and El Rosario, based on the 14 locally derived indicators (Rogé et al. 2014)

Team:

Community:

Production system:

Category	Indicator	Marginal	Acceptable	Optimal
Landscape	Territorial composition			
	Windbreaks			
	Field location			
	Soil conservation			
Farmer management	Crop rotation			
	Crop varieties			
	Polyculture			
	Soil amendments			
	Soil cultivation			
Soil quality	Spontaneous plants			
	Soil productivity			
	Soil organic matter			
	Soil depth			
	Soil texture			

At the scale of the farmers' landscape, Zaragoza farmers observed that vegetated borders and perennial vegetation with multiple uses mitigated exposure to extreme climatic events. Similarly, Coxcaltepec farmers recognized that heterogeneous and forested landscapes protected fields, bringing rain, retaining groundwater, accumulating soil organic matter, and controlling insect pests. El Rosario participants described that contour ditches capture soil and water, and that a slight slope to the contour ditches avoids flooding and breaching during heavy rainfall events.

Indicators of farmer management at the field-scale included the importance of crop genetic and species diversity for stabilizing overall yields given the variation in crop performance from year to year. The indicator of "soil amendments" was derived from farmer testimonies that synthetic fertilizer only improved crop yields with favorable rainfall; in drought years, synthetic fertilizer was ineffective and "even burned crops." Coxcaltepec participants recommended substituting synthetic fertilizers with various locally derived soil amendments, including animal manures, worm castings, forest humus, and human urine.

Soil quality was also described by farmers to affect the impact of climatic variability on agroecosystems. The three communities associated soil moisture retention with soil texture and depth. Generally, clayey soils were described as the most productive in drought years, but also difficult to cultivate in wet years. In contrast, farmers described sandy soils as the easiest to cultivate in wet years but also the least productive. Farmers considered deep soils, measured by how far the Egyptian plow entered the soil, are considered by farmers to be the most productive soils in both wet and dry years.

The resiliency evaluations conducted so far by the REDAGRES group suggest that agroecological strategies that

Table 2 Agroecological practices and their potential to enhance resiliency to climatic stresses through various effects on soil quality and water conservation

	Soil organic build up	Nutrient cycling	>Soil cover	Reduced ET	Runnoff reduction	>Water-holding capacity	>Infiltration	Microclimatic amelioration	Reduction of soil compactation	Reduction of soil erosion	>Hydrological regulation	>Water use efficiency	>Mycorrhizal network
Diversification													
• Mixed or intercropping			□	□	□			□	□	□		□	
• Agroforestry	□	□	□	□	□	□	□	□	□	□		□	
• Intensive silvopastoral system	□	□	□	□	□	□	□	□	□	□	□	□	□
• Crop rotation	□	□	□		□		□		□	□		□	
• Local variety mixtures			□									□	
Soil management													
• Cover cropping	□	□	□	□	□	□	□		□	□	□		
• Green manures	□	□	□	□	□	□	□		□	□		□	□
• Mulching													
• Compost applications	□					□							□
• Conservation agriculture (organic-no-till)			□	□	□		□		□	□		□	
Soil conservation													
• Contour farming					□		□		□	□	□		
• Grass strips/ living barriers			□		□		□			□	□		
• Terracing					□		□			□	□		
• Check dams along gullies					□		□			□	□		

enhance the ecological resiliency of farming systems are a necessary but not sufficient condition to achieve sustainability. The ability of groups or communities to adapt in the face of environmental stresses, social resilience must go hand in hand with ecological resiliency. To be resilient, rural societies must generally demonstrate the ability to buffer disturbance with agroecological methods adopted and disseminated through self-organization and collective action. Reducing social vulnerability through the extension and consolidation of social networks, both locally and at regional scales, can contribute to increases in agroecosystem resilience. As expressed in the risk formula, the vulnerability of farming communities depends on how well developed is their natural and social capital which in turn makes farmers and their systems more or less vulnerable to climatic shocks. Adaptive capacity refers to the set of social and agroecological preconditions that enable individuals or groups and their farms to respond to climate change in a resilient manner. The capacity to respond to changes in environmental conditions exists within communities to different degrees but not always all responses are sustainable. The challenge is to identify the ones that are in order to upscale them so that vulnerability can be reduced by enhancing the reactive capacity of communities to deploy agroecoecological mechanisms that allow farmers to resist and recover from climatic events. Social organization strategies (solidarity networks, exchange of food, etc.) used collectively by farmers in order to cope with the difficult circumstances imposed by such events are thus a key component of resiliency.

10 Conclusions

With certainty, some degree of climate change will have to be confronted by the agricultural sectors across all countries, thereby rendering adaptation imperative (Howden et al. 2007). It is essential that steps be taken to support farmers and households engaged in agriculture to cope with both the threat of climate variability as well as the challenges that climate change will pose on future livelihood opportunities. The launching of the Global Alliance for Climate Smart Agriculture (http://www.un.org/climatechange/summit/wp-content/uploads/sites/2/2014/09/AGRICULTURE-Action-Plan.pdf) at the recently held Climate Summit in New York, last September 2014, recognizes the imperative of adaptation, but its focus on sustainable improvements in productivity and building resilience principally emphasizing new innovations such as identification and development of climate smart genes for crop improvement, with little attention to traditional farming or agroecologically based approaches.

This is unfortunate given that traditional farming systems are repositories of a wealth of knowledge of a range of principles and measures that can help modern agricultural systems become more resilient to climatic extremes (Altieri and Toledo 2011). Many of these agroecological strategies listed in Table 2 can be implemented at the farm level to reduce vulnerabilities to climate variability. These include, crop diversification, maintaining local genetic diversity, animal integration, soil organic management, water conservation and harvesting, etc. A first key step is to understand the agroecological features of traditional and other agroecological farming systems that have stood the test of time (Dewalt 1994). The key question to address is what principles and mechanisms have allowed these systems to resist and/or recover from droughts, storms, floods, or hurricanes. These mechanisms can be deciphered using the methodologies described herein that assess the socio-ecological resiliency of farming systems.

The second step is to disseminate with increased urgency-derived resiliency principles and practices used by successful farmers as well as results from scientific studies that document the effectiveness of agroecological practices that enhance the resiliency of agroecosystems to extreme climatic events (droughts, hurricanes, etc.) (Stigter et al. 2005). The effective diffusion of agroecological technologies will largely determine how and how well farmers adapt to climate change. Dissemination to farmers in neighboring communities and others in the region can be done via field days, cross-visits, short seminars, and courses that focus on methods that explain how to assess the level of resiliency of each farm and what to do to enhance resistance to both drought and strong storms. However, the *Campesino a Campesino* methodology used by thousands of farmers in Mesoamerica and Cuba which consists of an horizontal mechanism of transfer and exchange of information is perhaps the most viable strategy to scale up agroecologically based adaptive strategies (Holt-Gimenez 1996; Rosset et al. 2011).

Most research focuses on the ecological resiliency of agroecosystems, but little has been written about the social resilience of the rural communities that manage such agroecosystems. The ability of groups or communities to adapt in the face of external social, political, or environmental stresses must go hand in hand with ecological resiliency. To be resilient, rural societies must generally demonstrate the ability to buffer disturbance with agroecological methods adopted and disseminated through self-organization and collective action (Tompkins and Adger 2004). Reducing social vulnerability through the extension and consolidation of social networks, both locally and at regional scales, can contribute to increases in agroecosystem resilience. The vulnerability of farming communities depends on how well developed is their natural and social capital which in turn makes farmers and their systems more or less vulnerable to climatic shocks (Nicholls et al. 2013). Most traditional communities still maintain a set of social and agroecological preconditions that enables their farms to respond to climate change in a resilient manner. Most large-scale farms have a low capacity to respond to changes in environmental conditions, because in the regions that they dominate the social fabric has been broken. The challenge will be to re-instate social organization and collective strategies in communities dominated by mid- to large-scale farms, thus, enhancing the reactive capacity of farmers to deploy agroecoecological mechanisms that allow to resist and/or recover from climatic events.

By pursuing adaptation through agroecology and food sovereignty frameworks, the livelihoods of more than 1.5 billion smallholders will continue not only to endure, but many of their systems will persist and serve as examples of sustainability which the world must urgently learn from. The transformation and democratization of the world's food system is the best way to adapt to climate change, while simultaneously eradicating hunger and poverty, as the root causes of inequality and environmental degradation are confronted head-on. International rural movements such as the Via Campesina provide the foundations to transform the current system, by promoting and scaling up agroecological principles and practices and promoting complex cooperative networks that transfer technical and political knowledge across international spheres, while challenging global institutions, international trade regimes, and the corporate control of the food system.

References

Adams MW, Ellingboe AH, Rossman EC (1971) Biological uniformity and disease epidemics. Bioscience 21:1067–1070. doi:10.2307/1295991

Adams RM, Hurd BH, Lenhart S, Leary N (1998) Effects of global climate change on agriculture: an interpretative review. Clim Res 11:19–30. doi:10.3354/cr011019

Adger WM (2000) Social and ecological resilience: are they related. Prog Hum Geogr 24:347–364. doi:10.1191/030913200701540465

Altieri MA (1999a) The ecological role of biodiversity in agroecosystems. Agric Ecosyst Environ 74:19–31. doi:10.1016/S0167-8809(99)00028-6

Altieri MA (1999b) Applying agroecology to enhance productivity of peasant farming systems in Latin America. Environ Dev Sustain 1:197–217. doi:10.1023/A:1010078923050

Altieri MA (2002) Agroecology: the science of natural resource management for poor farmers in marginal environments. Agric Ecosyst Environ 93:1–24. doi:10.1016/S0167-8809(02)00085-3

Altieri MA (2004) Linking ecologists and traditional farmers in the search for sustainable agriculture. Front Ecol Environ 2:35–42. doi:10.1890/1540-9295(2004)002[0035:LEATFI]2.0.CO;2

Altieri MA, Koohafkan P (2008) Enduring farms: climate change, smallholders and traditional farming communities. Environment and Development Series 6. Penang, Third World Network.

Altieri MA, Koohafkan P (2013) Strengthening resilience of farming systems: a key prerequisite for sustainable agricultural production. In: Wake up before it is too late: make agriculture truly sustainable now for food security in a changing climate. UNCTAD, TER13 Report, Geneva

Altieri MA, Nicholls CI (2004) Biodiversity and pest management in agroecosystems, 2nd edn. Haworth Press, New York. doi:10.2134/jeq2005.0729

Altieri MA, Nicholls CI (2013) The adaptation and mitigation potential of traditional agriculture in a changing climate. Clim Chang. doi:10.1007/s10584-013-0909-y

Altieri MA, Toledo VM (2011) The agroecological revolution in Latin America: rescuing nature, ensuring food sovereignity and empowering peasants. J Peasant Stud 38:587–612. doi:10.1080/03066150.2011.582947

Altieri MA, Lana MA, Bittencourt HV, Kieling AS, Comin JJ, Lovato PE (2011) Enhancing crop productivity via weed suppression in organic no-till cropping systems in Santa Catarina, Brazil. J Sustain Agric 35:855–869. doi:10.1080/10440046.2011.588998

Armillas P (1971) Gardens on swamps. Science 174:653–656. doi:10.1126/science.174.4010.653

Astier M, García-Barrios L, Galván-Miyoshi Y, González-Esquivel CE, Masera OR (2012) Assesing the sustainability of small-farmer natural resource management systems. A critical analysis of the MESMIS program (1995–2010). Ecol Soc 17(3):25. doi:10.5751/ES-04910-170325

Barrow CJ (1999) Alternative irrigation: the promise of runoff agriculture. Earthscan Publications, Ltd., London. doi:10.1017/S0014479700211083

Buckles D, Triomphe B, Sain G (1998) Cover crops in hillside agriculture: farmer innovation with Mucuna. International Development Research Center, Ottawa Canada. doi:10.1017/S0014479700232110

Bunch R (1990) Low-input soil restoration in Honduras: the Cantarranas farmer-to-farmer extension project. Sustainable Agriculture Gatekeeper Series SA23. IIED, London

Cabell JF, Oelofse M (2012) An indicator framework for assessing agroecosystem resilience. Ecol Soc 17(1):18. doi:10.5751/ES-04666-170118

Coakley SM, Scherm H, Chakraborty S (1999) Climate change and plant disease management. Annu Rev Phytopathol 37:399–426. doi:10.1146/annurev.phyto.37.1.399

Critchley WRS (1989) Building on a tradition of rainwater harvesting. Appropr Technol 16(2):10–12

Critchley WRS, Reij C, Willcocks TJ (2004) Indigenous soil and eater conservation: a review of the state of knowledge and prospects for building on traditions. Land Degrad Rehabil 5:293–314. doi:10.1002/ldr.3400050406

De Schutter O (2010) Report submitted by the Special Rapporteur on the right to food. UN General Assembly. Human Rights Council Sixteenth Session, Agenda item 3 A/HRC/ 16/49

Denevan WM (1995) Prehistoric agricultural methods as models for sustainability. Adv Plant Pathol 11:21–43. doi:10.1016/S0736-4539(06)80004-8

Dewalt BR (1994) Using indigenous knowledge to improve agriculture and natural resource management. Hum Organ 5:23–51

Diaz-Zorita M, Buschiazzo DE, Peineman N (1999) Soil organic matter and wheat productivity in the semiarid Argentine Pampas. Agron J 91:276–279. doi:10.2134/agronj1999.00021962009100020016x

Döll P (2002) Impact of climate change and variability on irrigation requirements: a global perspective. Climate Change 54:269–293. doi:10.1023/A:1016124032231

Easterling WE, Aggarwal PK, Batima P, Brander KM, Erda L, Howden SM, Kirilenko A, Morton J, Soussana JF, Schmidhuber J, Tubiello JN (2007) Food, fiber and forest products. In: Parry ML (ed) Climate Change 2007: impacts, adaptation and vulnerability: contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, pp 273–313

Erickson CL, Chandler KL (1989) Raised fields and sustainable agriculture in Lake Titicaca Basin of Peru. In: Browder JO (ed) Fragile lands of Latin America. Westview Press, Boulder, pp 230–243

Flores M (1989) Velvetbeans: an alternative to improve small farmers' agriculture. ILEIA Newsl 5:8–9

Folke C (2006) Resilience: the emergence of a perspective for social ecological systems analyses. Glob Environ Chang 16:253–267. doi:10.1016/j.gloenvcha.2006.04.002

Francis CA (1986) Multiple cropping systems. Macmillan, New York

Francis CA, Jones A, Crookston K, Wittler K, Goodman S (1986) Strip cropping corn and grain legumes: a review. Am J Altern Agric 1: 159–164. doi:10.1017/S0889189300001235

Franco J, Borras J, Vervest P, Isakson R, Levidow L (2014) Towards understanding the politics of flex crops and commodities: implications for research and policy advocacy. Transnational Institute, Netherlands

Fuhrer J (2003) Agroecosystern responses to combinations of elevated CO_2, ozone, and global climate change. Agric Ecosyst Environ 97(1–3):1–20. doi:10.1016/S0167-8809(03)00125-7

Garg N, Chandel S (2010) Arbuscularmycorrhizal networks: process and functions. Agron Sustain Dev 30:581–599. doi:10.1007/978-94-007-0394-0_40

Hatfield JL, Boote KJ, Kimball BA, Ziska LH, Izaurralde RC, Ort D, Thomson AM, Wolfe D (2011) Climate impacts on agriculture: implications for crop production. Agron J 103(2):351–370. doi:10.2134/agronj2010.0303

Heinemann JA, Massaro M, Coray DS, Agapito-Tenfen SZ, Wen JD (2013) Sustainability and innovation in staple crop production in the US Midwest. Int J Agric Sustain. doi:10.1080/14735903.2013.806408

Henao SJ (2013) Propuesta metodológica de medición de la resiliencia agroecológica en sistemas socio-ecológicos: un estudio de caso en Los Andes Colombianos. Agroecología 8(1):85–91

Hillel D, Rosenzweig C (2009) Handbook of climate change and agroecosystems: impacts, adaptation, and mitigation. Imperial College Press, London

Holt-Gimenez E (1996) The Campesino a Campesino movement: farmer-led, sustainable agriculture in Central America and Mexico. In: Food First Development Report No 10 Oakland, Institute of Food and Development Policy

Holt-Giménez E (2002) Measuring farmers' agroecological resistance after Hurricane Mitch in Nicaragua: a case study in participatory, sustainable land management impact monitoring. Agric Ecosyst Environ 93:87–105. doi:10.1016/S0167-8809(02)00006-3

Horwith B (1985) A role for intercropping in modern agriculture. Bioscience 35:286–291. doi:10.2307/1309927

Howden S, Soussana J, Tubiello F, Chhetri N, Dunlop M, Meinke H (2007) Adapting agriculture to climate change. Proc Natl Acad Sci 104(50):19691–19694. doi:10.1073/pnas.0701890104

IPCC (2014) Climate Change 2014: impacts, adaptation and vulnerability. IPCC Special Report, WGII

Jones PG, Thornton PK (2003) The potential impacts of climate change on maize production in Africa and Latin America in 2055. Glob Environ Chang 13:51–59. doi:10.1016/S0959-3780(02)00090-0

Kahn ZR, Ampong-Nyarko K, Hassanali A, Kimani S (1998) Intercropping increases parasitism of pests. Nature 388:631–632. doi:10.1038/41681

Koohafkan P, Altieri MA (2010) Globally important agricultural heritage systems: a legacy for the future. UN-FAO, Rome

Kurukulasuriya P, Rosenthal S (2003) Climate change and agriculture a review of impacts and adaptations. Climate Change Series Paper (91). World Bank, Washington

Landis DA, Gardiner MM, van der Werf W, Swinton SM (2008) Increasing corn for biofuel production reduces biocontrol services in agricultural landscapes. PNAS 105:20552–20557. doi:10.1073/pnas.0804951106

Lin BB (2007) Agroforestry management as adaptive strategy against potential microclimate extremes in coffee agriculture. Agric For Meteorol 144:85–94. doi:10.1016/j.agrformet.2006.12.009

Lin B (2011) Resilience in agriculture through crop diversification: adaptive management for environmental change. Bioscience 61:183–193. doi:10.1525/bio.2011.61.3.4

Lobell DB, Field CB (2007) Global scale climate–crop yield relationships and the impacts of recent warming. Environ Res Lett 2:1–7. doi:10.1088/1748-9326/2/1/014002

Lobell DB, Gourdji SM (2012) The influence of climate change on global crop productivity. Plant Physiol 160:1686–1697. doi:10.1104/pp.112.208298

Lobell DB, Schlenker W, Costa-Roberts J (2011) Climate trends and global crop production since 1980. Science 333:616–620. doi:10.1126/science.1204531

Loreau M, Naeem S, Inchausti P, Bengtsson J, Grime JP, Hector A, Hooper DU, Huston MA, Raffaelli D, Schmid B, Tilman D, Wardle DA (2001) Biodiversity and ecosystem functioning: current knowledge and future challenges. Science 294:804–808. doi:10.1126/science.1064088

Machado S (2009) Does intercropping have a role in modern agriculture? J Soil Water Conserv 64:55–58. doi:10.2489/jswc.64.2.55A

Magdoff F, Weil R (2004) Soil organic matter management strategies. In: Magdoff F, Weil R (eds) Soil Organic matter in sustainable agriculture. CRC Press, Boca Raton, pp 44–65. doi:10.1201/9780203496374.ch2

Mapfumo P, Adjei-Nsiah S, Mtambanengweb F, Chikowo R (2013) Giller KE (2013) Participatory action research (PAR) as an entry point for supporting climate change adaptation by smallholder farmers in Africa. Environ Dev 5:6–22. doi:10.1016/j.envdev.2012.11.001

Matthews B, Rivington M, Muhammed S, Newton AC, Hallett PD (2013) Adapting crops and cropping systems to future climates to ensure food security: the role of crop modelling. Glob Food Secur 2: 24–28. doi:10.1016/j.gfs.2012.11.009

Mijatovic D, Van Oudenhovenb F, Pablo Eyzaguirreb P, Hodgkins T (2013) The role of agricultural biodiversity in strengthening resilience to climate change: towards an analytical framework. Int J Agric Sustain 11(2):2013. doi:10.1080/14735903.2012.691221

Moyer J (2010) Organic no-till farming. Rodale Press, Emmaus

Murgueitio E, Calle Z, Uribea F, Calle A, Solorio B (2011) Native trees and shrubs for the productive rehabilitation of tropical cattle ranching lands. For Ecol Manag 261:1654–1663. doi:10.1016/j.foreco.2010.09.027

Natarajan M, Willey RW (1996) The effects of water stress on yields advantages of intercropping systems. Field Crop Res 13:117–131. doi:10.1016/0378-4290(86)90015-8

National Research Council, Committee on Genetic Vulnerability of Major Crops (1972) Genetic vulnerability of major crops. National Academies of Science, Washington

Netting RMC (1993) Smallholders, householders: farm families and the ecology of intensive, sustainable agriculture. Stanford University Press, Palo Alto. doi:10.1525/aa.1995.97.1.02a00530

Nicholls CI, Altieri MA (2013) Agroecologia y cambio climatico: metodologias para evaluar la resiliencia socio-ecologica en comunidades rurales. Red IberoAmericana de Agroecologia para el desarrollo de sistemas agricolas resilientes al cambio climatico (REDAGRES). Gama Grafica, Lima, p 91

Nicholls CI, Rios L, Altieri MA (2013) Agroecologia y resiliencia socioecologica: adaptandose al cambio climatico. Red IberoAmericana de Agroecologia para el Desarrollo de Sistemas Agricolas Resilientes al Cambio Climatico (REDAGRES), Medellin, p 207

Perfecto I, Vandermeer J, Wright A (2009) Nature's matrix: linking agriculture, conservation and food sovereignty. Earthscan, London. doi:10.1080/10440046.2010.519212

Petersen P, Tardin JM, Marochi F (1999) Participatory development of notillage systems without herbicides for family farming; the experience of the Center-South region of Paraná. In: Environment, development and sustainability. Kluwer Academic Publishers, Dordrecht. doi:10.1023/A:1010091208938

Philpott SM, Lin BB, Jha S, Brines SJ (2009) A multiscale assessment of hurricane impacts on agricultural landscapes based on land use and topographic features. Agric Ecosyst Environ 128:12–20. doi:10.1016/j.agee.2008.04.016

Pimentel D, Levitan LC (1986) Pesticides: amounts applied and amounts reaching pests. Bioscience 36:514–515. doi:10.2307/1310108

Ponti L, Gutierrez AP, Ruti PM, Dell'Aquila A (2014) Fine-scale ecological and economic assessment of climate change on olive in the Mediterranean Basin reveals winners and losers. Proc Natl Acad Sci U S A 111(15):5598–5603. doi:10.1073/pnas.1314437111

Porter JH, Parry ML, Carter TR (1991) The potential effects of climatic change on agricultural insect pests. Agric For Meteorol 57(1–3): 221–240. doi:10.1016/0168-1923(91)90088-8

Reij C (1991) Indigenous soil and water conservation in Africa. IIED Gatekeeper Series No 27, London

Reij C, Scoones I, Toulmin C (1996) Sustaining the soil: indigenous soil and water conservation in Africa. Earthscan, London. doi:10.1002/(SICI)1099-145X(199807/08)9:4<369::AID-LDR280>3.0.CO;2-H

Robinson RA, Wallace R (1996) Return to resistance: breeding crops to reduce pesticide dependence. Australas Plant Pathol 25:216–217. doi:10.1046/j.1365-3059.1998.00294.x

Rodale Institute (2012) The farming systems trial: celebrating 30 years. Rodale Press, Pennsylvania

Rogé P, Friedman AR, Astier M, Altieri MA (2014) Farmer strategies for dealing with climatic variability: a case study from the Mixteca Alta Region of Oaxaca. Agroecology and Sustainable Food Systems, Mexico. doi:10.1080/21683565.2014.900842

Rosenzweig C, Hillel D (2008) Climate change and the global harvest: impacts of El Nino and other oscillations on agroecosystems. Oxford University Press, New York

Rosset PM, Machín-Sosa B, Roque-Jaime AM, Avila-Lozano DR (2011) The Campesino-to-Campesino agroecology movement of ANAP in Cuba. J Peasant Stud 38(1):161–191. doi:10.1080/03066150.2010.538584

Stigter C, Dawei Z, Onyewotu L, Xurong M (2005) Using traditional methods and indigenous technologies for coping with climate variability. Clim Chang 70:255–271. doi:10.1007/1-4020-4166-7_12

Sutherst RW, Constable F, Finlay KJ, Harrington R, Luck J, Zalucki MP (2011) Adapting to crop pest and pathogen risks under a changing climate. Wiley Interdiscip Rev Clim Chang 2(2):220–237. doi:10.1002/wcc.102

Swiderska K (2011) The role of traditional knowledge and crop varieties in adaptation to climate change and food security in SW China, Bolivian Andes and coastal Kenya. IIED, London

Thornton PK (2003) The potential impacts of climate change in tropical agriculture: the case of maize in Africa and Latin America in 2055. Glob Environ Chang 13:51–59. doi:10.1016/S0959-3780(02)00090-0

Thrupp LA (1988) Cultivating diversity: agrobiodiversity and food security. World Resources Institute, Washington

Toledo VM, Barrera-Bassols N (2008) La Memoria Biocultural: la importancia ecologica de las sabidurıas tradicionales. ICARIA Editorial, Barcelona

Tompkins EL, Adger WN (2004) Does adaptive management of natural resources enhance resilience to climate change. Ecol Soc 9(2):10

Vandermeer J (1989) The ecology of intercropping. Cambridge University Press, Cambridge, p 237. doi:10.1017/CBO9780511623523

Vandermeer J, van Noordwijk M, Anderson J, Ong C, Perfecto I (1998) Global change and multi-species agroecosystems: concepts and issues. Agric Ecosyst Environ 67:1–22. doi:10.1016/S0167-8809(97)00150-3

Vigouroux J (2011) Biodiversity, evolution and adaptation of cultivated crops. Comptes Rendus Biol 334:450–457. doi:10.1016/j.crvi.2011.03.003

Ward NL, Masters GJ (2007) Linking climate change and species invasion: an illustration using insect herbivores. Glob Chang Biol 13(8): 1605–1615. doi:10.1111/j.1365-2486.2007.01399.x

West TD, Griffith DR (1992) Effect of strip-intercropping corn and soybean on yield and profit. J Prod Agric 5:107–110. doi:10.2134/jpa1992.0107

Wilken GC (1987) Good farmers: traditional agricultural resource management in Mexico and Central America. University of California Press, Berkeley. doi:10.1525/aa.1988.90.3.02a00840

Zhu Y, Fen H, Wang Y, Li Y, Chen J, Hu L, Mundt CC (2000) Genetic diversity and disease control in rice. Nature 406:718–772. doi:10.1038/35021046

Ziska LH, Dukes JS (2014) Invasive species and global climate change, CABI invasives series. CABI Publishing, Wallingford

Zougmoré R, Mando A, Stroosnijder L (2004) Effect of soil and water conservation and nutrient management on the soil-plant water balance in semi-arid Burkina Faso. Agric Water Manag 65:102–120. doi:10.1016/j.agwat.2003.07.001