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Strengthening resilience of modern farming systems: A key prerequisite for sustainable agricultural production in an era of climate change

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Today, a major challenge facing humanity is how to achieve a sustainable agriculture that provides enough food and ecosystem services for present and future generations in an era of climate change, increasing fuel costs, social tensions caused by food price hikes, financial instability and accelerating environmental degradation. The challenge is complicated by the fact that the majority of the world's arable land is under "modern" monoculture systems of maize, soybean, rice, cotton and others, which, due to their ecological homogeneity, are particularly vulnerable to climate change as well as biotic stresses.

A recent analysis by Heinemann et al. (2013) concluded that most major crops are impressively uniform genetically and impressively vulnerable to disease epidemics and extreme climatic events. This uniformity derives from powerful economic and legislative forces that favour monocultures and simplification. In fact, increased demand for corn grain as an ethanol feedstock is altering global agricultural landscapes and the ecosystem services they provide. For example, in four US Midwest states recent biofuel-driven growth in corn planting resulted in lower landscape diversity, decreasing the supply of pest 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).

Little has been done to enhance the adaptability of industrial agroecosystems to changing patterns of precipitation, temperature and extreme weather events (Rosenzweig and Hillel 2008). This realization has led many experts to suggest that the use of ecologically based management strategies that break the nature of monocultures and favour landscape heterogeneity may represent a robust path to increasing the productivity, sustainability and resilience of agricultural production while reducing undesirable socio-environmental impacts (Altieri 2002, De Schutter 2010).

Observations of agricultural performance after extreme climatic events during the last

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two decades have revealed that resilience to climate disasters is closely linked to the level of on-farm biodiversity (Lin 2011). Most scientists agree that a basic attribute for agricultural sustainability is the maintenance of agroecosystem diversity in the form of spatial and temporal arrangements of crops, trees, animals and associated biota. Increasingly, research suggests that agroecosystem performance and stability is largely dependent on the level of plant and animal biodiversity present in the system and its surrounding environment (Altieri and Nicholls 2004).

Biodiversity performs a variety of ecological services beyond the production of food, including recycling of nutrients, regulation of microclimate and local hydrological processes, suppression of undesirable organisms and detoxification of noxious chemicals, etc. Because biodiversity-mediated renewal processes and ecological services are largely biological, their persistence depends upon the maintenance of biological integrity and diversity in agroecosystems. In general, natural ecosystems appear to be more stable and less subject to fluctuations in yield and in populations of the organisms making up the community. Ecosystems with higher diversity are more stable because they exhibit:

- Higher resistance, or the ability to avoid or withstand disturbance, and
- Higher resilience, or the ability to recover following disturbance.

Biodiversity enhances ecosystem function because those components that appear redundant at one point in time may become important when some environmental change occurs. The key here is that when environmental change occurs, the redundancies of the system allow for continued ecosystem functioning and provisioning of services (Vandermeer et al. 1998).

Traditional farming systems, which still persist in many parts of the developing world, offer a wide array of management options and designs that enhance functional biodiversity in crop fields and consequently the resilience of agroecosystems (Uphoff 2002, Toledo and Barrera-Bassals 2009). This myriad of traditional systems comprise a globally important ingenious agricultural heritage that reflects the value of the diversity of agricultural systems adapted to different environments, and tell a fascinating story of the ability and ingenuity of humans to adjust and adapt to the vagaries of a changing physical and material environment from generation to generation. Whether recognized or not by the scientific community, this ancestral knowledge constitutes the foundation for actual and future agricultural innovations and technologies. The new models of agriculture that humanity will need in the immediate future should include forms of farming that are more ecological, biodiverse, local, sustainable and socially just. Therefore they will necessarily have to be rooted in the ecological rationale of traditional small-scale agriculture which represents long-established examples of successful and adaptive forms of agriculture (Koohafkan and Altieri 2010).

Small farms as models of resilience

In continuously coping through centuries with extreme weather events and climatic variability, farmers living in harsh environments in the regions of Africa, Asia and Latin America have developed and/or inherited complex farming systems managed in ingenious ways, allowing small farming families to meet their subsistence needs in the midst of environmental variability without depending much on modern agricultural technologies (Denevan 1995). The stubborn persistence of millions of hectares under traditional farming is living proof of a successful indigenous agricultural strategy and constitutes a tribute to the "creativity" of small farmers throughout the developing world (Wilken 1987). Today, well into the second decade of the 21st century, there are millions of smallholders, family farmers and indigenous people practising resource-conserving farming which is testament to the remarkable resilience of agroecosystems in the face of continuous environmental and economic change, while contributing substantially to agrobiodiversity conservation and food security at local, regional and national levels (Netting 1993).

Climate change can however pose serious problems to the majority of the 370 million of the poorest, who live in areas often located in arid or semi-arid zones, and in mountains and hills that are ecologically vulnerable (Conway 1997). In many countries, more people, particularly those at lower income levels, are now forced to live in marginal areas (i.e., floodplains, exposed hillsides, arid or semi-arid lands), putting them at risk from the negative impacts of climate vari-

ability. For these vulnerable groups, even minor changes in climate can have disastrous impacts on their lives and livelihoods. Implications can be very profound for subsistence farmers located in remote and fragile environments, where yield decreases are expected to be very large, as these farmers depend on potentially affected crops (e.g., maize, beans, potatoes, rice, etc.) for their food security. Despite the serious implications of these predictions, data only represents a broad-brush approximation of the effects of climate change on small-scale agriculture, as in many cases it ignores 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).

Three studies assessing agricultural performance after extreme climatic events reveal the close link between enhanced agrobiodiversity and resiliency to climate disasters. 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 neighbours. The survey, spearheaded by the Campesino a Campesino movement, mobilized 100 farmer-technician teams to carry out paired observations of specific agroecological indicators on 1,804 neighbouring 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 percent more topsoil, greater soil moisture and less erosion and experienced lower economic losses than their conventional neighbours (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. 2008). 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 percent compared to 90 or 100 percent in neighbouring monocultures. Likewise agroecologically managed farms showed a faster productive recovery (80-90 percent 40 days after the hurricane) than monoculture farms (Rosset et al. 2011).

All three studies emphasize the importance of enhancing plant diversity and complexity in farming systems to reduce vulnerability to extreme climatic events. Crop diversification in the form of polycultures and/or agroforestry systems represents a potential long-term strategy for farmers who are experiencing either hurricane risks and/or decreasing rainfall patterns and increasing temperature variability (Altieri and Nicholls 2013). Adding copious amounts of organic matter into soils (SOM) is particularly strategic when confronting droughts as SOM increases water holding capacity, infiltration, drainage, aeration and biological activity which enhances water use efficiency. Managing cover crops and green manures protects soil from erosion but also adds biomass, which in turn contributes to increased levels of SOM (Figure 1).

Given that many peasants commonly manage diversified farming systems, there is a need to re-evaluate indigenous technology as a key source of information on adaptive capacity centred on the selective, experimental and resilient capabilities of farmers in dealing with climatic change. Assessing the resilience features of diversified small farming systems and understanding the agroecological features of traditional agroecosystems is an urgent matter, as they can serve as the foundation for the design of climate-change-resilient agricultural systems (Altieri and Koohafkan 2008). These systems however are under threat as in many parts of the developing world, a convergence of interests between governments, donors and seed companies [e.g., the Alliance for a Green Revolution in Africa (AGRA)], combined with a historical preference for and dependence on maize or other single crops as primary staples, is leading to a narrowing of options for smallholder farmers, undermining the development of adaptive capacities in the longer term.

Restoring agrobiodiversity in modern agroecosystems

Since the onset of agricultural modernization, farmers and researchers have been faced with a main ecological dilemma arising from the homogenization of agricultural systems: an increased vulnerability of crops to insect pests and diseases, and now to climatic variability, both phenomena that can be devastating under uniform crop, large-scale monoculture conditions. Monocultures may have short-term economic

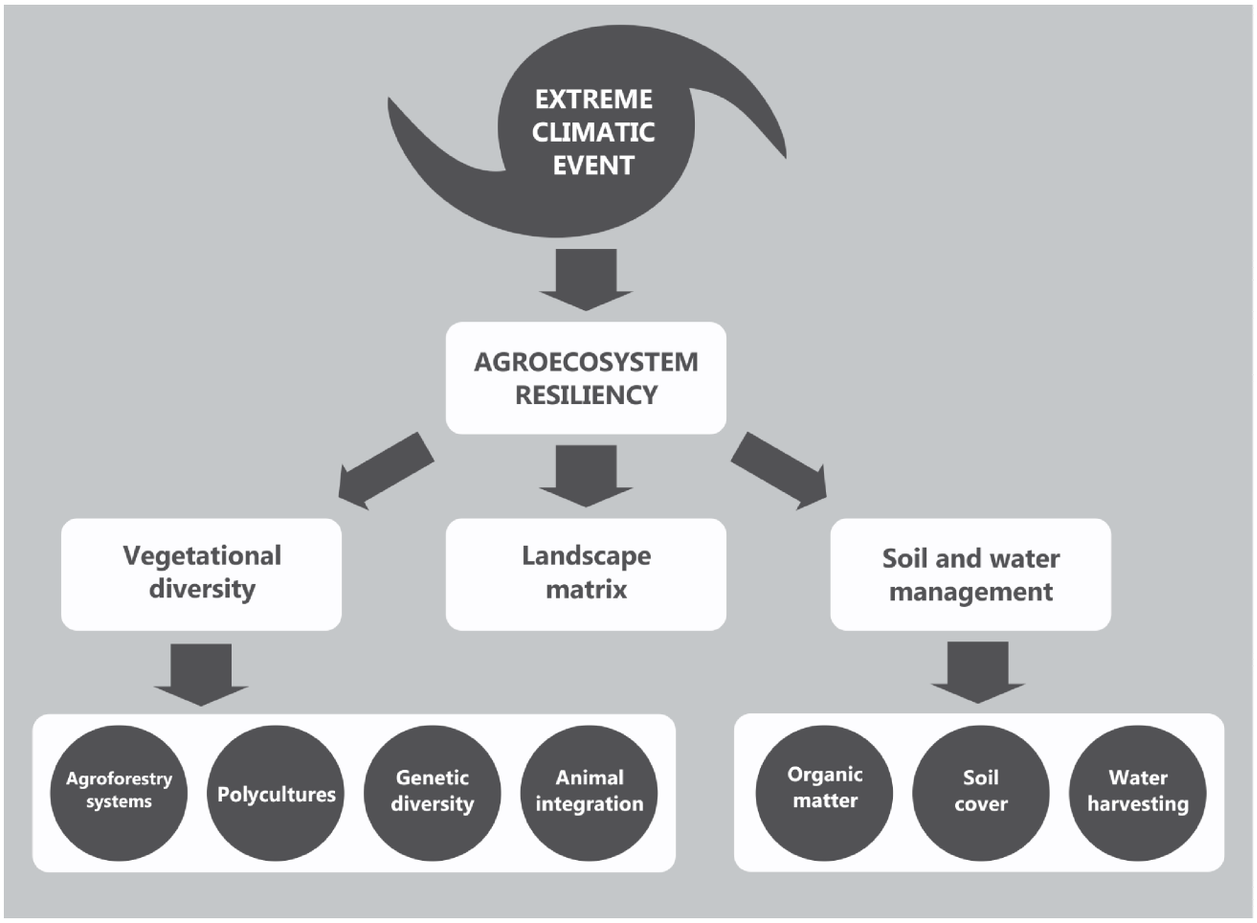

Figure 1. *Landscape, on-farm diversity and soil and water features that enhance the ecological resilience to extreme climatic events*

advantages for farmers, but in the long term they do not represent an ecological optimum. Rather, the drastic narrowing of cultivated plant diversity has put the world's food production in greater peril (Perfecto et al. 2009).

Given the new climate change scenarios, the search for practical steps to break the monoculture nature of modern agroecosystems and thus reduce their ecological vulnerability is an imperative. As traditional farmers have demonstrated with farming systems that stood the test of time, restoring agricultural biodiversity at the field and landscape level is key to enhancing resilience (Altieri and Nicholls 2013). The most obvious advantage of diversification is a reduced risk of total crop failure due to invasions by unwanted species and/or climatic variability as larger numbers of species reduce temporal variability in ecosystem processes in changing environments (Loreau et al. 2001). Studies conducted in grassland systems suggest that there are no simple links between species diversity and ecosystem stability. Experiments conducted in grassland plots conclude that functionally different roles represented by plants are at least as important as the total number of species in determining processes and services in ecosystems (Tilman et al. 2001). This latest finding has practical implications for agroecosystem management. If it is easier to mimic specific ecosystem processes rather than duplicating all the complexity of nature, then the focus should be placed on incorporating a specific biodiversity component that plays a specific role, such as a plant that fixes nitrogen, provides cover for soil protection or harbours resources for natural enemies of insect pests.

Contemporary notions of modern mechanized farming connote the necessity of monocultures. There is little question, however, that given sufficient motivation, appropriate technology could be developed to mechanize 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.

One such scheme 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 higher light intensities (Francis et al. 1986). Studies with corn and soybean strips four to 12 rows wide have demonstrated increased corn yields (+5 to +26 percent) and decreased soybean yields (-8.5 to -33 percent) as strips get narrower. Alternating corn and alfalfa strips provided greater gross returns than sole crops. Twenty-foot-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 percent or higher ($40 debt for every $100 of assets). Such a level has already been reached by more than 11-16 percent of the US Midwest farmers who desperately need to cut on costs of production by adopting diversification strategies.

The advantage of intercrops is that the two intercropped species do not compete for exactly the same resource niche and thereby tend to use resources in a complementary way. More precisely, the advantages of legume-cereal intercrops are often assumed to arise from the complementary use of nitrogen sources by the components of the intercrop. In grain legume-cereal intercrops grown at variable nitrogen levels, it has been observed that the grain legume has a higher interspecific competitive ability at lower soil nitrogen levels, while the cereal component competes better at higher soil nitrogen levels (Bedousac and Justes 2011). Intercropping legumes with cereals is a key diversification strategy not only because of the provision of nitrogen, but also because the mixtures enhance soil cover, smother weeds and increase soil microbial diversity such as vesicular arbuscular mycorrhizae (VAM) which facilitate phosphorus transfer and the availability of potassium, calcium and magnesium (Machado 2009). Moreover, increased vegetational diversity and the general biodiversity it induces at different trophic levels leads to more efficient natural control of pests and diseases in agroecosystems (Altieri and Nicholls 2004). In the case of adverse weather conditions like a delay in the onset of rains and/or failure of rains for a few days to weeks some time or other during the cropping period, an intercropping system provides advantages as at least one crop will survive to give economic yields, thereby providing for the necessary insurance against unpredictable weather. Polycultures exhibit greater yield stability and less productivity declines during a drought than monocultures. This was well demonstrated by Natarajan and Willey (1986) who examined the effect of drought on enhanced yields with polycultures by manipulating water stress on intercrops of sorghum (*Sorghum bicolor*) and peanut (*Arachis* spp.), millet (*Panicum* spp.) and peanut, and sorghum and millet. All the intercrops overyielded 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 overyielding actually increased with water stress, such that the relative differences in productivity between monocultures and polycultures became more accentuated as stress increased.

A strip intercropping system adapted to large-scale farms in the US Midwest

No-till row crop production is also promising given its soil conservation and improvement potential. Although these systems are highly dependent on herbicides, there are some organic farmers who practise 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 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 postplant 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.

When large-scale cropping systems are subject to organic management for at least three years (under either a manure-based organic system or a legume-based organic system), crops exhibit similar yields as the conventional fields, as demonstrated by a 30-year farming systems trial (FST) run by the Rodale Research Institute in Pennsylvania. Due to the fact that soil health (measured as carbon content) in the organic systems increased over time while the conventional systems remained essentially unchanged, as shown in Figure 2, organic corn yields were 31% higher than conventional in years of drought, a direct result of higher SOM and associated enhanced soil water storage (Rodale Institute 2012).

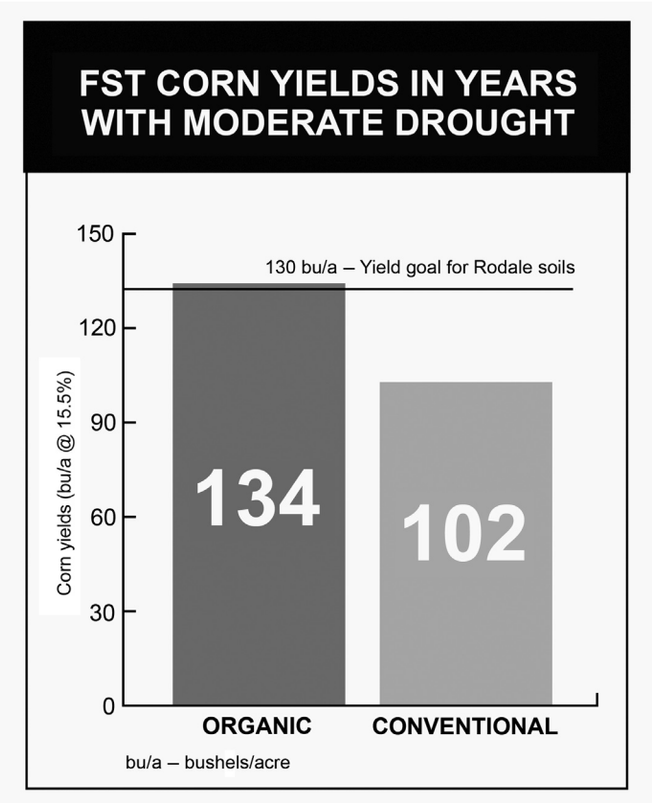

Figure 2. *Yields of corn under conventional and organic management in a drought year in Pennsylvania, USA (Rodale Institute 2012)*

Conclusions

There is general agreement at the international level on the urgency of promoting a new agricultural production paradigm in order to ensure the production of abundant, healthy and affordable food for an increasing human population. This challenge will need to be met in a world with a shrinking arable land base, less and more expensive petroleum, and increasingly limited supplies of water and nitrogen, and within a scenario of a rapidly changing climate, social tensions and economic uncertainty (IAASTD 2009). The only agricultural system that will be able to confront future challenges is one that will exhibit high levels of diversity and resilience while delivering reasonable yields and ecosystem services. Many traditional farming systems still prevalent in the developing world can serve as models of sustainability and resilience as they thrive without agrochemicals and their levels of biodiversity confer production stability and provide many services to farmers and society at large (www.giahs.org).

Resilience in agricultural systems is a function of the level of diversity and enhanced soil organic matter within the agricultural ecosystem. It is therefore essential that strategies for adaptive response to climate change focus on breaking the monoculture nature of modern agroecosystems. Small changes in the management of industrial systems, such as intercropping and/or use of rotational cover cropping in no-till systems, can substantially enhance the adaptive capacity of cropping systems. Weather extremes, including local drought and flooding, are predicted to become more common with rapid climate change. Environmentally responsible water management will therefore be a critical part of a sustainable agriculture future. Agroecological strategies for conserving water

include choosing water-efficient crops, resource-conserving crop rotations, soil-health-enhancing practices and adoption of risk-minimizing intercropping systems.

Most research focuses on the ecological resiliency of agroecosystems – that is, on the ability of such systems to absorb perturbations – or their speed of recovery from climatic disturbances. Little has been written about the social resilience of the rural communities that manage such agroecosystems. Social resilience has been defined as the ability of communities to withstand external shocks to their social infrastructure. 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 regionally, can contribute to increases in agroecosystem resilience. As seen in Figure 3, the vulnerability of farming communities depends on how well developed their natural and social capital is, 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 much in areas dominated by large-scale farms where the social fabric has been broken. The challenge will be to reinstate social organization and collective strategies in communities dominated by mid- to large-scale farms, thus enhancing the reactive capacity of farmers to deploy agroecological mechanisms that allow resistance to and/or recovery from climatic events.

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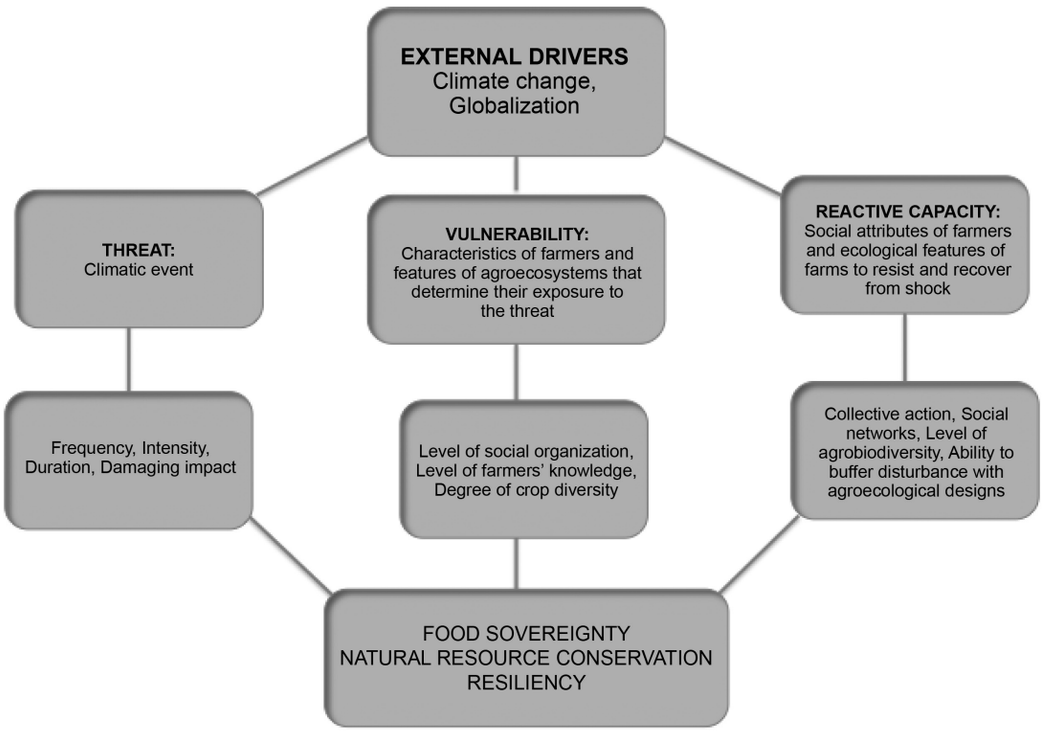

Figure 3. *Factors affecting the vulnerability of rural communities to climatic events and their reactive capacity to enhance socio-ecological resiliency (Altieri and Nicholls 2013)*

The above is a revised and expanded version of a Commentary article by Altieri and Koohafkan in the United Nations Conference on Trade and Development (UNCTAD)'s *Trade and Environment Review 2013: Wake Up Before It Is Too Late – Make Agriculture Truly Sustainable Now for Food Security in a Changing Climate* (United Nations publication UNCTAD/DITC/TED/2012/3, 2013).

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