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The role of agricultural biodiversity in strengthening resilience to climate change: towards an analytical framework

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Traditional agricultural communities manage biodiversity at various scales, creating dynamic landscape mosaics of fields, gardens, orchards, pastures and ecosystem patches. Agricultural biodiversity and associated traditional knowledge are essential to the climate change resilience of these landscapes, but their roles are largely overlooked by researchers and policy makers. A review of 172 case studies and project reports from around the world shows that agricultural biodiversity contributes to resilience through a number of, often combined, strategies: the protection and restoration of ecosystems, the sustainable use of soil and water resources, agro-forestry, diversification of farming systems, various adjustments in cultivation practices and the use of stress-tolerant crops and crop improvement. Using social–ecological systems theory as a conceptual framework, these practices are examined to identify indicators of resilience in agricultural landscapes. The indicators are a first step in the development of a framework for assessing and building climate change resilience, intended both for local communities and for the scientists and organizations working closely with them. The framework can be used to (i) identify biodiversity management practices and social institutions that can be encouraged as ways to strengthen resilience, (ii) monitor the resilience of a landscape/community over time and (iii) aggregate and compare data across communities and landscapes.

Keywords: social–ecological systems; agricultural landscapes; adaptation; indicators

1. Introduction

Traditional agricultural systems provide sustenance and livelihood to more than 1 billion people (Altieri 2002, Nori et al. 2005, Howard et al. 2009). They often integrate soil, water, plant and animal management at a landscape scale, creating mosaics of different land uses. These landscape mosaics, some of which have existed for hundreds of years, are maintained by local communities through practices based on traditional knowledge accumulated over generations. Well-known examples are the landscapes that depend on traditional irrigation technologies ranging from paddy fields in the tropics to qanats (underground water supply systems) in the drylands. These, like many other less known traditional practices, persist in areas where modern technologies are either unsuitable or inaccessible. Many traditional agricultural systems, in particular home gardens and agroforestry, are rich in agricultural biodiversity (Halladay and Gilmour 1995, Trinh et al. 2003, Wezel and Bender 2003, Eyzaguirre and Linares 2004, Hemp 2006, Jarvis et al. 2007, Robson and Berkes 2011). Agricultural biodiversity encompasses the variety and variability of animals, plants and micro-organisms used directly or indirectly for food and agriculture. It provides various ecosystem services (e.g. pollination and nutrient cycling) and

Minimizing biodiversity loss and increasing the sustainability and resilience of agricultural systems have been identified as major challenges (e.g. IAASTD 2009, Pretty et al. 2010). Climate change threatens the livelihood of rural communities (Easterling et al. 2007), often in combination with pressures coming from demographic change, insecure land tenure and resource rights, environmental degradation, market failures, inappropriate policies and the erosion of local institutions (O’Brien and Leichenko 2000, Adger et al. 2004, Morton 2007). Empowering local communities and combining farmers’ and external knowledge have been identified as some of the tools for meeting these challenges (IAASTD 2009). Local and indigenous communities themselves have voiced the need to develop local strategies to build climate change resilience and secure livelihoods in their traditional territories (Galloway McLean et al. 2009, PAR 2009), yet their experiences have received little attention in academia and among policy makers (Salick and Byg 2007). Given the recognized role that biodiversity plays in the resilience of systems (e.g. Rockström et al. 2009), surprisingly little work has been done to understand the link between agricultural biodiversity and climate change resilience. The 4th report of the Intergovernmental Panel on Climate Change (Adger et al. 2007) and the literature on adaptation options for agriculture (e.g. Howden et al. 2007) do not consider agricultural biodiversity and associated traditional knowledge. Reasons for this oversight may range from a general absence of trans-disciplinary approaches to understanding climate change adaptation to a lack of political and commercial interest in supporting biodiversity-rich agro-ecosystems. With the focus on new technologies promising one-size-fits-all solutions in the form of stress-resistant crop varieties, ‘old’ practices (e.g. cultivation of locally adapted crops and landraces) have received little attention in agricultural research. Another reason why the role of agricultural biodiversity and traditional knowledge is overlooked is that information on this topic is largely scattered. The present review is an attempt to collect and synthesize this information and outline areas of further research.

Most existing tools and frameworks for assessing climate change’s impact on agriculture use modelling to combine various types of data (e.g. climate and crop data and climate change scenarios) (Lane and Jarvis 2007). In addition to uncertainties surrounding climate change modelling and the limitations of coarse-scale predictions of climate change implications on agricultural productivity (Burton and Lim 2005, Gornall et al. 2010), these tools and frameworks obscure factors relevant for resilience at the landscape or community level. They do not capture the complex relationship between agricultural biodiversity and resilience, and are therefore unlikely to be beneficial to agricultural communities who base their risk management and adaptation strategies on the use of biodiversity. A more inclusive range of social, economic, political and environmental factors that confer resilience have been discussed by several authors (Kates 2000, Adger et al. 2004, Eriksen et al. 2005, Owuor et al. 2005, Eriksen and Kelly 2007), but have not yet been integrated into a common framework.

Our approach focuses on local strategies to maintain and increase land productivity in the face of climate change through the sustainable use of agricultural biodiversity. We seek to elucidate the linkages between resilience and agricultural biodiversity by examining traditional agricultural landscapes as linked social–ecological systems (SESSs), whose resilience is defined as consisting of three characteristics: the capacity to (i) absorb shocks and maintain function, (ii) self-organize...
and (iii) learn and adapt (Carpenter and Brock 2008). Based on the perspective of SESs theory, the underlying premise in our approach is that landscape resilience depends not only on biodiversity at different scales (from the genetic to ecosystem level) and synergistic interactions at and between different scales (e.g. interactions between wild and cultivated landscape components), but also, and to a large extent, on human agency and institutions (Berkes et al. 2000, 2002).

We present the results of a review of 172 project reports and cases studies that describe the use of agricultural biodiversity and associated knowledge in strengthening resilience to climate change-related stresses. The review identifies the main resilience-strengthening practices and how they vary across different agro-ecological environments. Building on this information, the paper examines these practices in the context of SESs, and proposes a set of tentative resilience indicators. These efforts are the first step in the development of an analytical framework for assessing and building resilience at the landscape level.

2. Scope and method of the review

The review was guided by the question: What are the most common uses of agricultural biodiversity and associated traditional knowledge in strengthening resilience to climate change-related stresses? It covered 172 case studies and reports from Africa, Central and South America, Asia and the Pacific (Figure 1). The case studies and reports are listed in Supplemental Table 1, and have been shared through an open group at Mendeley.com (available at http://www.mendeley.com/groups/1422633/climate-change-resilience-in-traditional-agricultural-landscapes/papers/).

With very few peer-reviewed sources available on the topic, the scope of the review was broadened to include different types of reports and non-peer-reviewed articles. The reports and articles describe responses initiated by communities as well as local initiatives supported or guided by external parties. In some cases, it is difficult to distinguish between community-led and externally driven practices. The selection of articles and case studies is biased in that most sources are written in English and by third parties (rarely by (indigenous) communities themselves), and that many are presented as project results and may portray activities more positively than warranted by reality. These limitations and the difficulty of comparing accounts written in different

Figure 1. Locations of reviewed case studies and project reports.
formats with varying levels of detail were partly overcome by focusing on the most common responses to climate change, defined as those that are applied in 5%, or more, of the total number of reviewed initiatives.

The main resilience-strengthening practices identified in the review were grouped according to the scale at which biodiversity is managed and the type of environment in which they are practiced. As for scale, following the importance given to understanding the spatial scales of biodiversity management in agricultural landscapes by proponents of the landscape approach (Buck et al. 2007, Scherr and McNeely 2007, 2008), practices were divided into three levels: the landscape, the farming system and the species/or variety. Second, to understand the variation of practices across different agro-climatic environments, the initiatives were categorized into four groups: (i) tropical and subtropical; (ii) mountain (subtropical and high mountain regions of the Andes and Himalayas); (iii) arid, semi-arid and tropical semi-arid; and (iv) coastal and small islands.

3. Results: resilience-strengthening practices

Climate change affects agriculture in a number of ways. In most cases, farmers face increasingly erratic rainfall, altered seasonal weather patterns and a more frequent occurrence of adverse weather events, floods and droughts. These stresses have a direct impact on land productivity (e.g. by affecting agricultural crops) and an indirect impact via water and soil resources (e.g. exacerbating soil erosion). Practices that strengthen resilience to these stresses are summarized in Table 1, showing the uses of biodiversity at three different scales: the landscape, the farming system and the species or variety. Figure 2 shows how the choice of practices varies across different environments. Some variation is apparent, most notably the high importance of

<table>
<thead>
<tr>
<th>Resilience-strengthening practices (the number of examples)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Scale</strong></td>
</tr>
<tr>
<td><strong>Landscape</strong></td>
</tr>
<tr>
<td>Ecosystem protection and restoration (64)</td>
</tr>
<tr>
<td>• Watershed restoration</td>
</tr>
<tr>
<td>• Reforestation</td>
</tr>
<tr>
<td>• Habitat protection</td>
</tr>
<tr>
<td>Adjustments in water and soil management (72)</td>
</tr>
<tr>
<td>• Water harvesting and irrigation</td>
</tr>
<tr>
<td>• Re-vegetation, tree planting and other measures against soil erosion.</td>
</tr>
<tr>
<td><strong>Farming system</strong></td>
</tr>
<tr>
<td>Diversification (82)</td>
</tr>
<tr>
<td>• Cultivation of a higher diversity of crops</td>
</tr>
<tr>
<td>• Agro-forestry</td>
</tr>
<tr>
<td>Adjustments in agricultural practices (88)</td>
</tr>
<tr>
<td>• Soil fertility improvement (e.g. cover crops and mulching)</td>
</tr>
<tr>
<td>• Crop calendar adjustment (change of planting dates) and the cultivation of new types and combinations of crops (e.g. intercropping)</td>
</tr>
<tr>
<td>• Rainwater harvesting (e.g. infiltration pits and planting basins)</td>
</tr>
<tr>
<td><strong>Species/variety</strong></td>
</tr>
<tr>
<td>Use of resistant species and varieties and stress-tolerance improvement (83)</td>
</tr>
<tr>
<td>• Use, conservation and distribution of resistant species, varieties and breeds (e.g. drought- and salt- and water-logging-resistant species and varieties of crops) and short-duration crops</td>
</tr>
<tr>
<td>• Stress-tolerance improvement through selection and breeding techniques</td>
</tr>
</tbody>
</table>
ecosystem restoration in coastal areas. Overall variation, however, is not large, partly because the majority (65%) of all cases combine measures at different scales (i.e. from landscape-level to species-focused measures) to address multiple effects of climate change (e.g. droughts followed by floods). For example, Ulsrud et al. (2008) show that communities in Nepal, Ethiopia and Nicaragua use a variety of measures, from ecosystem rehabilitation to the stress-tolerance improvement of local varieties. These different measures help mitigate the loss of yield or livestock in two ways: first, by moderating the effects of climate change on agro-ecosystems through practices that regulate micro-climate and improve soil conditions (e.g. agro-forestry) and, second, by ‘adjusting’ the agro-ecosystems to changing climate (e.g. through cultivation of new crop mixtures). The following paragraphs describe and illustrate the main resilience-strengthening practices at each scale. Figure 3 shows cross-scale linkages between these practices in a landscape.

At the landscape scale, agricultural activities create mosaics of land uses (i.e. home gardens, fields, orchards, forest patches, fishing grounds and pastures). Degradation of ecosystems in and adjacent to these agricultural landscapes, caused by population pressure, overexploitation and the expansion of agricultural areas, is decreasing climate change resilience. Ecosystem protection and restoration, as resilience-strengthening measures, can help minimize and buffer against the effects of droughts, floods, sea-level rise and extreme weather events. Examples include reforestation of hillsides and mangroves, rehabilitation of pasturelands and restoration of wetlands, peatlands, watersheds and coral reefs. In coastal areas, ecosystem (often: mangrove) restoration helps to mitigate the risks associated with extreme weather events and reduce the negative impact of salt-water intrusion and coastal erosion. Of less importance in coastal areas, but prevalent in other environments, is the rehabilitation of water and soil resources, particularly in areas experiencing drought. These efforts often build on traditional techniques and include rainwater harvesting, irrigation systems, field terraces and landscape re-vegetation. Edwards et al. (2011) describe how revived or improved traditional practices combined with new approaches were successful in the Tigray region of Ethiopia, where benefits from landscape restoration included increased yields, raised water tables and improved soil fertility.
At the farming system level, practices that strengthen resilience aim to reduce yield losses through the cultivation of a larger number of species (diversification), crop–livestock integration and various adjustments (e.g. crop rotation, irrigation and sustainable soil management). Diversification through the integration of trees into production systems is a strategy employed in 32.5% of all 172 cases in areas subjected to drought, delayed onset of rainy seasons, floods, extreme weather events and erratic rainfall. The presence of trees and shrubs, among other benefits, provides windbreaks, shade and shelter for crops and animals, and regulates soil moisture and temperature. Diversification of farming systems is often combined with adjustments in agricultural practices and adoption of low-input methods for soil fertility improvement and water conservation. Examples of adaptation to altered seasonal patterns and erratic rainfall are changes in cropping calendars and crop types (Wajih 2008). The use of tamarind (*Tamarindus indicus*) leaves to reduce soil salinity in Jaffna, Sri Lanka, (Vakeesan et al. 2008) is one of a myriad of low-input methods identified as helpful in dealing with and adapting to climate change-related stresses.

At the level of species/variety, resilience is strengthened through the cultivation of fast-growing and stress-tolerant crop species and varieties, and individual and collective efforts to

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**Figure 3.** Cross-scale linkages between resilience-strengthening practices at different levels: 1. *Synergistic interactions between practices at the landscape and farming system levels*. Diversified farming systems that support biodiversity through the sustainable use of land, water and other resources receive, in return, ecosystem services that minimize the effect of extreme weather and climate events on agricultural production (e.g. flood protection and drought mitigation). 2. *Links between the farming system and species or variety levels*. The maintenance of and access to agricultural biodiversity enable rehabilitation, diversification and adaptation of farming systems.
protect and replenish diversity in agricultural systems. For example, in Niger and Mali, among the growers of pearl millet and sorghum there is an increasing frequency in the use of fast-growing varieties, which are better suited to conditions of erratic and decreasing rainfall (Kouressy et al. 2003, Bezançon et al. 2009). In India, in areas experiencing flooding and salinization of agricultural land and freshwater reserves, several community seed banks have been established to improve access to salt- and flood-tolerant varieties of rice. Furthermore, a number of communities have undertaken and participated in projects to improve the stress tolerance of their crops through selection and breeding techniques. A community in Nepal has reintroduced traditional rice landraces into its fields and established a seed bank that conserves 69 rice varieties, some with drought-resistant and lodging-tolerant characteristics, which were used in a participatory plant breeding programme (Ulstrud et al. 2008).

4. Discussion: traditional agriculture landscapes as adaptive SESs

The choice, development and implementation of practices described in the previous section depend on a number of social factors discussed below. The use of agricultural biodiversity by local communities in strengthening resilience can be conceived as an adaptive SES (Howard 2010), in which human activities are coupled and integrated with ecological processes in a dynamic way (Berkes et al. 2000, Folke et al. 2002, Folke 2004, Pilgrim and Pretty 2010). The social factors that determine resilience of SESs are summarized in the concept of adaptive capacity, referring to the ability of humans to deal with change (e.g. climate change) in their environment by observation, learning and altering their interactions (e.g. adjusting (biodiversity) management) (Folke et al. 2002). Folke et al. (2003) describe adaptive capacity as consisting of four elements that function across temporal and spatial scales: ‘learning to live with change and uncertainty, nurturing diversity for resilience, combining different types of knowledge for learning, and creating opportunity for self-organization towards sustainability’. In the following paragraphs, these elements will be examined in a discussion on how the practices identified in this review correspond to the previously mentioned characteristics of resilience in SESs: the capacity to (i) absorb shocks and maintain function, (ii) self-organize and (iii) learn and adapt (Carpenter and Brock 2008).

4.1. Capacity to absorb shocks and maintain function

For communities practising traditional types of agriculture, the landscape’s function of providing subsistence is central to their choice of biodiversity management practices. The negative effects of climate change on landscape functioning can be reduced through ecosystem restoration and the conservation of soil and water resources. The implementation of conservation and restoration activities, however, depends on the existence of local networks and institutions that mediate collective action. This is illustrated by an example from Rajasthan, where in the past, patches of vegetation considered as sacred groves helped to protect water sources crucial to agriculture (Mukhopadhyay 2009). The degradation of sacred groves and associated water management schemes severely impaired water availability. Two decades ago, a local initiative started in the Alwar district of Rajasthan with an aim to reinstate traditional rainwater-harvesting systems. Thousands of small-scale irrigation systems have been re-built contributing to improved water availability for irrigation and watershed restoration at the landscape scale, despite recurrent drought and other stresses (Scherr and McNeely 2008, Gupta and Anjali 2011).

The success of resilience-strengthening measures such as diversification, stress-tolerance improvement and the use of resilient species, varieties and breeds is influenced by, among a range of factors, the existence of exchange networks within and between communities (e.g.
local markets and seed exchange systems), which determine the availability and accessibility of material needed for their implementation (e.g. seeds and seedlings). The cases reviewed in this paper show that improving access to diverse seeds through, for example, the establishment of community seed banks is particularly important in places where climate change and other forces (e.g. pest outbreaks, market forces or agricultural policies) have resulted in a significant loss of diversity.

4.2. Capacity for self-organization
Self-organization refers to the ability of a community, or groups within a community or society, to choose, develop and implement solutions consistent with their needs, resources or agricultural traditions. Gender and social inequality and other types of discrimination and exclusion, as well as ethnic and political conflicts and wars, can hinder the capacity for self-organization of women and other vulnerable groups. Women’s activities of providing food and water to their families are directly affected by climate change. The ability to self-organize enables them to use their specialized knowledge about biodiversity use and conservation (e.g. knowledge of seed saving and edible wild plants) in resilience-strengthening initiatives. For indigenous communities, resilience to climate change is intrinsically linked with their efforts to protect traditional ways of subsistence and cultural heritage. Many small-scale farmers and indigenous groups face difficulties in obtaining or safeguarding land ownership rights (Deininger 2011). The ability to access (ancestral) lands and to maintain or acquire the agricultural biodiversity needed for strengthening climate change resilience may depend on the degree of autonomy that communities have in relation to commercial exploitation of resources, and agricultural and development policies. Autonomy, in turn, is partly determined by how local institutions guide collective action, either to further the aims of the community itself or to counter those of external parties that threaten its autonomy. Illustrating this is the Potato Park in the Peruvian Andes, where some 300 community members requested the restitution of 400 ancestral potato varieties from a genebank to help them reinforce their traditional adaptation mechanism of cultivation of up to 150 potato varieties in a single field (Argumedo and Stenner 2008, Argumedo and Wong 2010).

4.3. Capacity for learning and adaptation
The management of agricultural biodiversity is a dynamic process of continuous innovation that integrates new experiences and information into ‘traditional’ knowledge and practices. Accumulated over generations, this knowledge contains long-term perspectives about climate and adaptation and can help discern periodic, cyclical and long-term changes. In our review, local knowledge of crop, seed, animal, soil and water management, especially in harsh and stress-prone environments, emerged as valuable in strengthening resilience. The extent to which this knowledge is sufficient to deal with the pace of current climatic changes clearly has its limits. Yet, partly because climate change does not always create new but often exacerbates existing problems (e.g. increasing the frequency, duration and severity of drought and flood events), past experiences are valuable in planning future responses. In at least 20% of all cases, traditional practices have been revived because they are considered more productive under changing agro-ecological conditions than conventional agricultural methods. In other cases, to maintain agricultural production under changing conditions, traditional practices have been abandoned, adjusted, improved or combined with novel methods in the process of innovation. Here again, social networks within and between communities and farmer-to-farmer interaction (formal and informal) play an important role by facilitating innovation and the diffusion of, for example, novel techniques and seeds.
Table 2: Proposed indicators of climate change resilience in traditional agricultural landscapes.

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Measure</th>
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<tbody>
<tr>
<td>1. Maintenance of species and varietal diversity</td>
<td>The number of cultivated crop species or varieties per household/community. Existence of local classification systems of agricultural biodiversity. Existence of community seed banks.</td>
</tr>
<tr>
<td>Species and varietal diversity provides material for adaptation and a source of increasingly needed varieties and breeds with stress-resistant traits.</td>
<td></td>
</tr>
<tr>
<td>2. Heterogeneity in agricultural landscape</td>
<td>The number of landscape components (cultivated and wild): forest patches, riparian forests, fishing grounds, pasturelands, water-harvesting areas, home gardens, cultivated fields, orchards and fallows.</td>
</tr>
<tr>
<td>Different components of landscape mosaics provide various ecosystem services (e.g. trees provide windbreaks and control soil erosion).</td>
<td></td>
</tr>
<tr>
<td>3. Ecosystem protection and sustainable use of resources</td>
<td>Rates of ecological degradation as a result of pollution, land conversion or overexploitation. Efficiency of use and conservation of water, soil and other resources.</td>
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<tr>
<td>The protection and restoration of watersheds, forest and coastal ecosystems help to regulate hydrology and microclimate and thereby provide a buffer against extreme weather and climate events.</td>
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<tr>
<td>4. Availability and exchange of seeds, seedlings and livestock</td>
<td>Existence of community seed banks, tree nurseries, seed and animal fairs, local markets and formal and informal seed exchange networks.</td>
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<tr>
<td>The availability of a diversity of local and new species, varieties and breeds and other material is required for resilience-strengthening strategies (e.g. seedlings for reforestation).</td>
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<tr>
<td>5. Transmittance of traditional knowledge across generations</td>
<td>Use of traditional knowledge, technologies and practices by young members of a community. Percentage of a population (by age and gender) speaking local language. Continued practice of agricultural traditions.</td>
</tr>
<tr>
<td>Resource management strategies are often built on traditional knowledge, which is site-specific and embodied in local languages, cultural values, social institution and agricultural traditions.</td>
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</tr>
<tr>
<td>Innovation in management strategies, access to new types of information and the exchange of knowledge help to address challenges that cannot be solved with traditional techniques.</td>
<td></td>
</tr>
<tr>
<td>7. Existence of local networks and institutions</td>
<td>Existence of institutions managing land, food and water resources (village councils, customary laws, etc.); safety and exchange networks; festivals and community media.</td>
</tr>
<tr>
<td>Local networks and institutions facilitate collective action and enable exchange and dissemination of knowledge, skills, information and material between different communities and individuals within communities.</td>
<td></td>
</tr>
<tr>
<td>8. Gender</td>
<td>Women’s involvement in (communal) decision-making and agricultural innovation. Equal access to land and information.</td>
</tr>
<tr>
<td>Making the concerns, views and knowledge of women an integral part of the development of resilience-strengthening practices contributes to the effectiveness of these practices, particularly with respect to food and water supply at the household level.</td>
<td></td>
</tr>
<tr>
<td>Autonomy with respect to local development and the choice of land management and agricultural practices allows communities to develop and adopt practices corresponding to their needs and available resources.</td>
<td></td>
</tr>
</tbody>
</table>
5. Further research: indicators of resilience against climate change

In the above discussion, local institutions, such as seed exchange networks, community seed banks and resource management initiatives, emerged as important elements of resilience. These local institutions are embedded in larger contexts of environmental, social and political change. This makes the assessment of resilience, at any level of complexity, a considerable challenge. Nevertheless, common elements of resilience in traditional agricultural landscapes can be discerned from the review and the discussion, providing a set of potentially relevant resilience indicators (Table 2). These indicators will be tested in participatory field studies to develop an analytical tool for local communities as well as scientists and organizations working closely with them. The indicators may be used in a practical manner to help identify practices and social institutions that can be strengthened as ways to build resilience, or in a research- or project-oriented context to monitor the resilience of a landscape/community over time, and aggregate and compare data across communities and landscapes.

6. Conclusion

In traditional agricultural landscapes, strategies to strengthen climate change resilience include (i) at the scale of the landscape, the protection and restoration of ecosystems and the sustainable use of soil and water resources; (ii) at the scale of the farming system, diversification, agro-forestry and various adjustments in practices; and (iii) at the level of the species or variety, stress-tolerance improvement and the use of resistant species, varieties and breeds. The resilience of these landscapes can be described as ‘a dynamic interplay between persistence and change’ (Carpenter and Brock 2008); it requires the maintenance of agricultural biodiversity, but depends on the continuous innovation. The set of indicators proposed in this paper lays the ground for further research towards an analytical framework aimed to help in the development of local strategies for strengthening climate change resilience through innovation, the sustainable use of agricultural biodiversity, community management of genetic resources, and the encouragement of beneficial interactions between cultivated and wild areas.

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