Integrating Climate Change Adaptation and Mitigation Through Agroforestry and Ecosystem Conservation

Johanna Matocha, Götz Schroth, Terry Hills, and Dave Hole

Abstract Climate change adaptation and mitigation are usually the objects of separate projects, but in this review we argue that in agricultural contexts, there are often technical and financial advantages in pursuing them simultaneously. This is because (1) adaptation planning is often necessary for mitigation (i.e., carbon sequestration) planning, especially for assessing future climate risks to mitigation investments, (2) certain land-use interventions can have both adaptation and mitigation benefits, and (3) carbon finance can help in supporting adaptation which still tends to be underfunded. Agroforestry and ecosystem conservation are key approaches in the integration of climate change adaptation and mitigation objectives, often generating significant co-benefits for local ecosystems and biodiversity. Synergies between climate change adaptation and mitigation actions are particularly likely in projects involving income diversification with tree and forest products, reduction of the susceptibility of land-use systems to extreme weather events, improvement of soil fertility, fire management, wind breaks, and the conservation and restoration of forest and riparian

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J. Matocha
The Paradigm Project, 619 N Cascade Ave,
Suite 110, Colorado Springs, CO 80903, USA
e-mail: johanna.matocha@gmail.com

G. Schroth (✉)
Federal University of Western Pará,
C.P. 513, 68109-571 Santarém, Pará, Brazil
e-mail: goetz.schroth@gmail.com

T. Hills
Conservation International, 2/204 Kent St,
New Farm, QLD 4005, Australia
e-mail: t.hills@conservation.org

D. Hole
Conservation International, 2011 Crystal Drive,
Arlington, VA 22202, USA
e-mail: d.hole@conservation.org

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corridors, wetlands, and mangroves. On the other hand, trade-offs between adaptation and mitigation are possible when fast-growing tree monocultures for mitigation conflict with local tree and forest uses, making livelihoods more vulnerable, when trees are planted in water-scarce areas conflicting with local water uses, and in some cases when "climate-smart" agroforestry practices conflict with the need for agricultural intensification to produce increasing amounts of food for a growing population. Such conflicts need to be avoided through careful, site-specific, and participatory project development. We conclude that adaptation considerations should be included in mitigation project planning and integrated adaptation and mitigation activities should be prioritized in carbon markets and policy formation.

Keywords AFOLU (agriculture, forestry, and other land use) • Ecosystem-based adaptation • Income diversification • Land-use planning • Resilience of livelihoods

Introduction

Overwhelming evidence is now available to show that human-driven climate change is occurring, and that its harmful effects will most directly affect those least developed nations that are vulnerable to declining food and water security (Parry et al. 2007). The effects of climate change have already begun to threaten food and water supplies, putting low-income farmers and others immediately dependent on natural resources most at risk (UNEP 2009). We may also be starting to see the effects of a warmer world in increased occurrence and intensity of flooding, droughts, and storms (Goswami et al. 2006; Parry et al. 2007). Given projections that extreme weather and changes in baseline values of variables such as temperature and rainfall will reduce crop productivity and food security, as well as result in ecosystem alteration and disruption (Parry et al. 2007; Schroth et al. 2009; Fagre et al. 2009; Williams and Jackson 2007), there is an urgent need to identify and implement adaptation measures to increase the resilience of livelihoods and ecosystems to climate change.

At the same time, climate change mitigation must be intensified to limit the extent of alterations to the Earth's climate, in the hope of keeping them within a range in which adaptation is still feasible. Current levels of greenhouse gas (GHG) emissions will very likely result in continued temperature increases, potentially triggering positive feedbacks in the Earth system that may overwhelm the capacity, especially of poor societies, to effectively adapt (Lenton et al. 2008). Thus, the more successful mitigation activities are, the more time there will be to develop and implement suitable adaptation initiatives and the less acute those initiatives will have to be (Parry et al. 2007).

Recent observational data show current GHG emission trends to be near the upper end of the worst-case scenario (A1F1) presented in the International Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (IPCC 2000), indicating that governments and the international community must take their commitments to both adaptation and mitigation far more seriously than they have done thus far (Anderson and Bows 2008). Indeed, it appears increasingly unlikely that mitigation efforts currently proposed will be effective in keeping global temperature increases at or below 2 °C and atmospheric carbon dioxide levels at or below 450–550 ppm, values that are often assumed to represent the thresholds to dangerous climate change (Ramanathan and Feng 2008), though they are based on political consensus rather than scientific evidence (Anderson and Bows 2008). It is therefore imperative to explore the potential to mainstream climate change adaptation and mitigation across the full spectrum of climate-sensitive development activities.

Given the pressing concern over food security in the next 20 years due to increased population and at least locally decreased food supply resulting from climate stresses (Lobell et al. 2008), agricultural systems must be a key focus of adaptation strategies to climate change. There are 450 million small farms in the world, which support over two billion people through subsistence, rain-fed agriculture (Cook 2009). In addition to being one of the sectors most vulnerable to climate change, agriculture is also a major contributor to its causes, producing approximately 14% of GHG emissions, including through agricultural expansion (IPCC 2007; Le Quéré et al. 2009). It is the largest producer (58%) of anthropogenic non-CO_2 emissions, emitting 84% of all N_2O and 47% of CH_4 (Beach et al. 2008). Seventy-four percent of all agricultural emissions originate in developing countries (FAO 2008), and these figures are expected to increase due to rising population and changing dietary preferences (Beach et al. 2008). These data show that agriculture not only is a key sector for climate change adaptation but also has great potential for contributing to climate change mitigation. It is therefore important to look for synergies and trade-offs between climate change adaptation and mitigation in agriculture and related land-use activities.

Recent work indicates that land use and land-use change have direct impacts on, for example, soil moisture availability, length of growing season, and local and regional precipitation patterns (Pyke and Andelman 2007; Mahmood et al. 2009), making agriculture and other land uses central to adaptation efforts in developing countries. At the same time, land-based carbon mitigation schemes, such as avoided deforestation, reforestation, and agricultural and agroforestry practices that sequester carbon in vegetation and soil, can make a significant contribution to global climate change mitigation while providing project financing and a potential source of income to resource-poor farmers (FAO 2009).

Though managed forests and agroforests typically contain less carbon than primary forests, agroforestry systems can, under certain conditions, increase landscape carbon stocks by providing sustainable alternatives to short-fallow slash-and-burn agriculture or unshaded tree crops. For example, one set of studies found that agroforestry systems contained carbon stocks of 50–75 $\mathrm{Mg\,C\,ha^{-1}}$, while row crops contained <10 $\mathrm{Mg\,C\,ha^{-1}}$ (Verchot et al. 2007; Montagnini and Nair 2004), pointing to the significant potential for agroforestry to increase on-farm carbon stocks.

Albrecht and Kandji (2003) also found that agroforestry systems can have a wide range of carbon stocks ranging from 29 to 228 Mg C ha^{-1} with a median value of 95 Mg C ha^{-1}. Values quoted by Luedeling et al. (2011) for dryland Africa fall mostly in the lower part of this range, as would be expected. A prediction of the potential for carbon storage and sequestration in agroforestry systems for southern Mexico showed that reforestation, improved tropical fallows, and coffee plantations may, in 25 years, store approximately 130–181 Mg C ha^{-1} in aboveground biomass (Soto-Pinto et al. 2009). Shifting from pasture without trees to pastures with scattered trees in the same region also substantially increased carbon stocks (Soto-Pinto et al. 2009). According to Nair et al. (2010), annual rates of above- and belowground carbon storage in agroforestry systems range from 0.29 to 15.21 Mg ha^{-1} $year^{-1}$. Following a detailed analysis of the management factors influencing climate change mitigation and adaptation, Nair (2012) gives a SWOT (strengths, weaknesses, opportunities, and threats) analysis of the role of agroforestry systems in that regard.

Traditionally, climate change adaptation and mitigation are pursued by different groups in society through separate projects (Klein et al. 2005), with adaptation often focusing on engineering, land-use planning, and broader developmental approaches to reducing future risks of flooding, water scarcity, or other weather-related risks without specifically integrating mitigation objectives (Leary et al. 2008; Agnew and Woodhouse 2011). Climate change mitigation, on the other hand, usually emphasizes carbon efficiency in industrial processes, transport, housing, energy generation, etc., as well as, more recently, reforestation and forest conservation for C sequestration with little explicit reference to possible adaptation benefits, although Metz (2010) briefly mentions opportunities for mitigation-adaptation synergies and Klein et al. (2005) discuss the institutional complexities of achieving such synergies. In this review we argue that, especially in land use, there are strong opportunities for synergies, but also risks of trade-offs between climate change adaptation and mitigation. We therefore review possibilities for combined adaptation and mitigation activities, focusing on the interrelation of adaptation (e.g., disaster risk reduction and increased resilience for food and water security) and carbon sequestration in above- and belowground biomass and organic matter, with a focus on "Agriculture, Forestry and Other Land Use" (AFOLU) projects (Box 1). We focus on activities that have the added benefits of simultaneously conserving biodiversity and ecosystem services, characteristics that we consider essential for successful adaptation and sustainable development. We first review reasons for integrating climate change adaptation and mitigation, then analyze potential synergies and trade-offs between adaptation and mitigation for a range of situations, followed by recommendations and the identification of research needs. In considering these linkages, the breadth of responses that can be considered "adaptation" needs to be qualified. Depending on the specifics of the local climate exposures, sensitivity of the local people and economies to those exposures, and their adaptive capacity, adaptation responses may cover a wide range of activities that seek to enhance the technical capacity of people, strengthen capacities of institutions, incorporate climate change risk into various levels of decision making, or promote and disseminate knowledge and learning (UNDP 2010).

Box 1 Agriculture, Forestry and Other Land Use (AFOLU) Under the Clean Development Mechanism

The Clean Development Mechanism (CDM) is one of the flexibility mechanisms created under the Kyoto Protocol and allows industrialized countries to finance emissions-avoiding projects in developing countries and receive credit for such efforts. The CDM contributes to the reduction of GHG emissions, but also supports sustainable development in host countries through the mobilization of financial resources and the transfer of cleaner technologies. Under the CDM, Agriculture, Forestry, and Other Land Use (AFOLU) projects can contribute to the reduction of GHG emissions while providing benefits to rural communities in developing countries, potentially improving rural livelihoods by linking the poorest people with the global carbon market. In UNFCCC discussions, AFOLU has essentially the same meaning as land use, land-use change, and forestry (LULUCF) but integrates agriculture within LULUCF sectors (UNDP 2008). Current AFOLU project categories under the Voluntary Carbon Standard (VCS) include Afforestation, Reforestation and Revegetation (ARR), Agricultural Land Management (ALM), Improved Forest Management (IFM), Reducing Emissions from Deforestation and forest Degradation (REDD), and Peatland Rewetting and Conservation (PRC) (VCS 2011)

Why Integrate Climate Change Adaptation and Mitigation?

Both technical and financial reasons exist to look for synergies between climate change adaptation and mitigation:

- In some cases, successful adaptation is a precondition for successful mitigation. For example, where climate scenarios suggest that the climate will become hotter and drier and potentially more prone to wildfires, improved fire management (an adaptation intervention) reduces the risk from wildfire to projects that pursue climate change mitigation through forest conservation and reforestation (Schroth et al. 2009). The same argument would apply where adaptation measures attempt to reduce flooding risks in a wetter climate, thereby also benefiting reforestation projects at flood-prone sites. Also, future adaptation responses to climate change may influence the availability of sites for mitigation projects, for example, where agricultural land, roads, or settlements need to be relocated from increasingly flood-prone valleys or coastal areas to higher ground, affecting the availability of upland sites for reforestation. In a changing climate, adaptation planning is thus an essential input to the sustainable design of mitigation projects, especially where future climate conditions will affect viability and permanence of mitigation efforts.

Fig. 1 Mixed agroforests of coffee (*Coffea arabica*) and ornamental palms (*Chamedorea* sp.) in the Sierra Madre de Chiapas, Mexico, that provide diversified income, soil protection, and carbon storage (Photo: G. Schroth)

- In many cases, the same interventions generate both adaptation and mitigation benefits, so integration can be achieved with little or no additional cost. As explained above, both adaptation and mitigation projects require information on climate scenarios, land use, and community practices, providing an opportunity for joint planning of adaptation and mitigation projects. For example, the recent development of a climate change adaptation strategy for coffee-producing communities in the higher parts of the Sierra Madre de Chiapas in southern Mexico highlighted the importance of complex vegetation (both forest and coffee shade canopies) as a proven means to reduce the damage from hurricanes, whose intensity and severity is predicted to increase, while simultaneously sequestering carbon (Philpott et al. 2008; Schroth et al. 2009; Fig. 1). Similarly, the restoration of mangrove forests to reduce the exposure of coastal communities to storm surges has obvious climate change mitigation benefits and potential for carbon marketing. Adaptation actions involving the restoration and sustainable management of ecosystems as part of adaptation strategies have been termed "ecosystem-based adaptation" (EbA – Box 2).

Box 2 Ecosystem-Based Adaptation (EbA)

Ecosystem-based adaptation is the use of biodiversity and ecosystem services as part of an overall adaptation strategy to help people adapt to the adverse effects of climate change (Convention on Biological Diversity 2009). “As one of the possible elements of an overall adaptation strategy, ecosystem-based adaptation uses the sustainable management, conservation, and restoration of ecosystems to provide services that enable people to adapt to the impacts of climate change. It aims to maintain and increase the resilience and reduce the vulnerability of ecosystems and people in the face of the adverse effects of climate change.” (IUCN 2009)

- On the other hand, trade-offs between adaptation and mitigation are also possible – for example, where fast-growing tree monocultures reduce the availability of native forest resources that may be important for the resilience of local communities, or where greater vegetation cover through mitigation-based reforestation leads to reduced downstream water availability due to increased transpiration in an increasingly dry climate (Hayward 2005). An approach to climate change adaptation and mitigation that systematically assesses the interrelationships between both objectives will maximize synergies while avoiding or minimizing such trade-offs.
- Financial reasons also exist for considering climate change adaptation and mitigation in their mutual context. Presently, international funding commitments for climate change adaptation are growing (currently at around 20% of the climate funding pledge of over USD26 billion across 23 global funds; Climate Funds Update 2011), but are still widely considered to be insufficient to address the increasing vulnerabilities to climate change in poor countries, and the future of this adaptation funding is still unclear. In this situation, if adaptation co-benefits could be generated through climate change mitigation projects, the emerging carbon markets for land-based carbon projects could help bridge the funding gap while more sustainable solutions to the problem of adaptation funding are being pursued. This has been recognized, for example, by the authors of the Carbon, Community and Biodiversity Standard, who have systematically attempted to integrate adaptation measures as a best practice in mitigation projects (CCBA 2008).

Establishing a precise picture of synergies between adaptation and mitigation activities is a first step in the process of crafting policies and metrics that will enable more comprehensive and effective approaches to climate change and better assessment of the outcomes of these activities. Figure 2 shows how the integration of adaptation and mitigation strategies could be achieved at the level of project planning. In the following two sections, we briefly review synergies and trade-offs between climate change adaptation and mitigation for specific project types.

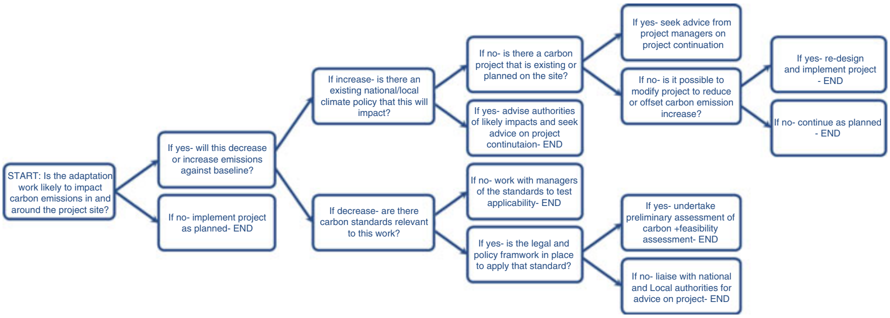

Fig. 2 Decision tree for the inclusion of climate change mitigation into the design of a climate change adaptation project

Synergies Between Climate Change Adaptation and Mitigation

Integrated adaptation and mitigation activities are intended to fortify the resilience of land-use systems to the adverse effects of climate change while at the same time reducing the negative and unsustainable impacts of human activity on the climate. Identifying and prioritizing these activities require a multifaceted analysis that takes into account the potential of a land-use system for carbon sequestration, the ability of an activity to increase the resilience of that system to climate change, and the capacity of local communities to implement and maintain a project, as well as the benefits they would derive from it. Verchot et al. (2007) coined the term "sustainagility" to highlight the dynamic element of adaptation within the assessment of a system's permanence and increased resilience. The following sections will discuss some types of interventions with potential for integrating ecosystem-based adaptation (see Box 2) and mitigation. Key messages are summarized in Table 1.

Income Diversification with Tree or Forest Products

Principle: Income diversification with tree or forest products can reduce the vulnerability of resource-poor farmers to climate and market shocks (adaptation) while increasing landscape carbon stocks (mitigation).

The diversification of livelihoods that spread risk over several crops or activities is continually listed as the most effective means of increasing resilience to climate change, especially for resource-poor farmers in the developing world (Douglas 2009; Eakin 2005; Lin et al. 2008; Schroth et al. 2009). While wealthier farmers with access to investment capital and possibly government subsidies may adapt to climate change through infrastructure improvements (e.g., irrigation) and crop insurance, resource-poor farmers may have to rely on diversification to reduce the impact of weather and climate uncertainty and prepare for gradual change in their

Table 1 Summary of practices offering synergies between climate change adaptation and mitigation

Practice	Adaptation benefits	Mitigation benefits	Key references
Income diversification with tree or forest products (e.g., through integrating trees in crop and pasture systems, reforestation of unproductive farm land)	Reduced impact of weather and climate uncertainty by spreading it over several crops or activities with different sensitivities; preparation for gradual change in land-use systems to match climate change	Increased carbon storage in biomass and soil	Douglas (2009), Eakin (2005), Kumar and Nair (2011), Lin et al. (2008), Montagnini and Nair (2004), Schroth et al. (2009)
Conservation agriculture and agroforestry (e.g., intercropping, cover cropping, live fences, shade trees)	Improved water retention and filtration; improved resilience of crops to drought; reduced hurricane susceptibility	Increased carbon storage in biomass and soil	Bradshaw et al. (2007), FAO (2008), Holt-Giménez (2002), Lin et al. (2008), Scherr and Sthapit (2009)
Practices to increase soil carbon storage (e.g., minimum tillage, use of compost and manure)	Reduced soil erosion and water pollution; increased soil water retention and biological soil function	Increased soil carbon storage	Nair et al. (2009, 2010), Nair (2012), Scherr and Sthapit (2009)
Reduced nitrogen fertilizer use (e.g., use of leguminous plants, targeted fertilizer application)	Reduced dependence on costly external inputs	Reduced greenhouse gas emissions from fertilizer production, transport, and soil (N_2O)	Lin et al. (2008), Nair et al. (2009), Scherr and Sthapit (2009)
Fire management	Reduced damage from wildfire	Increased carbon storage in biomass and soil	ProAct (2008), Scherr and Sthapit (2009), Schroth et al. (2009), Soto-Pinto et al. (2009)
Windbreaks	Crop protection from wind especially during drought; reduced wind erosion; income from tree products	Increased carbon storage in biomass and soil	Jindal et al. (2008), Klein et al. (2007), ProAct (2008)
Restoration and conservation of forest corridors including riparian forests	Protection against flooding and landslides; water and fisheries conservation; increased pollination and pest control; conservation of terrestrial and aquatic biodiversity	Increased carbon storage in biomass and soil	FAO (2008), Hannah et al. (2008), Heller and Zavaleta (2008), Pyke and Andelman (2007), Scherr and Sthapit (2009)
Mangrove conservation and restoration	Increased protection of coastal areas to erosion and storm surges; increased fish habitat; production of timber and non-timber products	Increased carbon storage in biomass and soil	Mukherjee et al. (2010), ProAct (2008)
Wetlands conservation	Regulation of water flows; water filtration	Carbon storage in peat and sediment	Battin et al. (2009), FAO (2008), Nyman (2011), ProAct (2008)

land-use systems (Schroth et al. 2009). If diversification is achieved by integrating trees into land-use systems and conserving production forests, it also benefits mitigation. Building of markets and supply chains and clarification of legal issues, for example, about tree ownership, are key issues in diversification, as are education, capacity building, and community involvement (Douglas 2009). Given the uncertainty associated with specific impacts that are likely to be experienced in a changing climate, diversification presents a way of spreading risk "on the ground" without requiring expensive modeling or infrastructure interventions. Agroforestry systems that include non-timber or timber trees in land-use systems are an important way of diversifying income. Examples of this include the smallholder forest gardens in Indonesia that integrate tree-based production of fruit, craftwood, timber, and other tree products with the production of field crops such as cassava (*Manihot esculenta*), maize (*Zea mays*), and rice (*Oryza sativa*; Roshetko et al. 2002). Under pressure from increasing ecosystem degradation, many cocoa (*Theobroma cacao*) farmers in West Africa now diversify into rubber (*Hevea brasiliensis*) which is more resilient than cocoa to poor soil and climate conditions (Ruf 2008). Where such systems are implemented as an alternative to degraded grassland or annual crops, there is also an increase in sequestered carbon.

The integration of trees with livestock production in silvopastoral systems can also provide a range of benefits. These systems can provide enhanced fodder and shelter for livestock, potentially improving their productivity in a hotter climate, and at the same time increase carbon stocks above those of conventional pastures (Ibrahim et al. 2004; Hänsela et al. 2009; Somarriba et al. 2012). Many of the land use and agricultural techniques already discussed can also incorporate livestock. The integration of livestock into mixed land uses will be increasingly important as the demand for animal protein grows and may be particularly attractive as a diversification option where the climate is becoming drier and less suitable for certain crops (Toni and Holanda 2008). One successful program combining mitigation and adaptation activities with benefits for both ecosystems and smallholders is the Regional Integrated Silvopastoral Ecosystem Management Project, which provided payments for ecosystem services (PES) to farmers in Colombia, Costa Rica, and Nicaragua during 2003–2007. In that case, PES helped to make the program attractive to land owners and provided a form of income diversification. The project also connected forest fragments (potentially benefitting biodiversity) and had a high rate of adoption after the end of the payments (Svadlenak-Gomez 2009).

Reducing the Susceptibility to Extreme Weather Events

Principle: Conservation agriculture and agroforestry can reduce the susceptibility to extreme weather events while increasing landscape carbon stocks.

Management practices such as intercropping, cover cropping, live fences, and shade trees can help to improve soil and water quality and reduce runoff and erosion (Lin et al. 2008). Farms using conservation practices have also been shown to be more resilient to extreme events. A study by Holt-Giménez (2002) on the role of agricultural practices in the aftermath of Hurricane Mitch in Nicaragua showed “agroecological” farms using soil conservation measures (contour plowing and planting, terracing, composting, etc.), integrated pest management, and agroforestry (live fences, vegetative strips, etc.) to have more topsoil and higher field moisture, more vegetation within the system, and lower economic losses compared to “conventional” farms that did not use such practices. A similar study by Tengo and Belfrage (2004) in Tanzania found that improved management through intercropping led to higher resistance to pest outbreaks and improved water conservation, increasing resilience to drought. Increased soil porosity from tree roots and shade provided by leaf cover, coupled with reduced runoff, can also enhance resilience to drought according to this study. Lin (2007) showed that shading results in lower evapotranspiration of coffee trees and mitigates microclimate extremes, which are expected to increase in a changing climate (Fig. 1).

Agricultural systems incorporating trees may also help protect against extreme events such as floods and storms with the incorporation of trees into grasslands providing greater slope stability in slip-prone lands (FAO 2008). Though there is debate about the degree of protection from landslides provided by forests and trees (FAO 2008; ProAct 2008), there is conclusive evidence that the majority of landslips and shallow slope failures occur on land cleared for crops, indicating that the shear resistance provided by tree roots can significantly decrease the risk of slippage caused by rainfall over extended periods. Such slippages not only harm agricultural productivity but also dump sediment into watercourses harming water quality and aquatic life and may be a direct danger to human settlements and infrastructure. Removal of tree cover accelerates runoff, thus increasing the risk of flooding in the rainy season and drought in the dry season. Although forests do not provide adequate protection against damage caused by high-magnitude storm events, they can help mitigate the severity of flooding and flood damage (Bradshaw et al. 2007). The forest floor and soil of riparian forest buffers trap sediment from upslope areas and can filter fertilizer and pesticides from runoff water. Forests in water catchments are thus particularly important for helping to provide clean drinking water to urban areas. Trees can also improve the water catch in cloud or fog situations, for example, in higher elevation cloud forest ecosystems (Postel and Thompson 2005). Agroforestry systems in strategic positions can approximate forests as regulators of sediment in water flow while providing marketable products (FAO 2008). Landscapes with year-round vegetative cover reduce runoff and can maintain most or all watershed functions, even when under (well-managed) productive use (Scherr and Sthapit 2009).

Improved Soil Quality

Principle: Best management practices for improved soil quality increase soil carbon stocks and aid in adaptation.

Management practices to increase organic matter in soil and improve soil nutrient availability provide an effective synergy of adaptation and mitigation strategies (Nair 2012). Increasing organic matter in soil increases water-holding capacity, nutrient availability, and carbon sequestration (Foley et al. 2005). Soil meanwhile constitutes an estimated 90% of agriculture's sequestration potential (FAO 2009), serving as the third largest carbon pool on the Earth's surface (Scherr and Sthapit 2009).

Practices such as minimum or zero tillage are shown to increase soil water retention, reduce erosion, improve carbon sequestration below ground, and often increase yields, as discussed in more detail by Nair (2012). Agroforestry systems both improve soil quality and are good candidates for soil carbon storage due to practices accompanying the management of agroforestry systems, such as returning harvested material to the soil (Montagnini and Nair 2004). The amounts of carbon sequestered in the soil under agroforestry systems can be substantial, adding to their aboveground carbon sequestration (Nair et al. 2009, 2010). Nair et al. (2010) reported C stocks ranging from 30 to 300 Mg ha^{-1} in the soil to 1 m depth.

Soil is concurrently an important source of nitrogen emissions, and these are influenced by management practices. Nitrous oxide (N_2O) has about 300 times the warming capacity of CO_2 and directly results from the use of inorganic fertilizer, emitting the equivalent of more than 2 billion t of CO_2 each year (Scherr and Sthapit 2009). To reduce emissions by minimizing the need for inorganic fertilizers, Scherr and Sthapit (2009) recommend using compost, green manure (where crops grown during fallows are plowed into the soil), nitrogen-fixing crops, cover crops and trees, and livestock manure. Planting crops and grasses that slow nitrification to a level that is still consistent with good crop growth, as in experiments with *Brachiaria* grass in Africa, would not only help reduce greenhouse gas emissions (N_2O) but also lower water pollution from nitrate, while enhancing productivity through more efficient use of fertilizer (CGIAR 2009). Such practices result in more closed nutrient cycles, thereby reducing farmers' dependence on external nutrient inputs and increasing their resilience in the face of fluctuating input prices (Lin et al. 2008; Nair et al. 2009).

Fire Management

Principle: Fire management is a precondition for successful mitigation and is a key adaptation measure in a hotter, drier climate.

Fire plays an important and natural, but potentially damaging, role in forest growth and management, with implications for both adaptation and mitigation. Fire is central in creating and maintaining ecological processes such as forest succession, as in the case of species that will not germinate unless they are exposed to fire (e.g., pines). However, fires set for agricultural or pasture management often get out of control and can release substantial quantities of carbon into the atmosphere, threaten the lives and livelihoods of communities, and destroy natural ecosystems. In Indonesia, the third largest emitter of GHG after the USA and China, forest fires are a major cause of deforestation; in 1997–1998, fire in that region contributed 2.1 billion t of CO_2 to worldwide emissions (Scherr and Sthapit 2009).

Where climate change increases the risk of crop failure and encourages the conversion of agricultural areas into pasture, fire use is likely to increase, with concomitant increase in the risk of wildfires. As an example, this scenario could occur in the near future in coffee-producing areas in Mesoamerica that are predicted to become marginal for coffee owing to increased drought, more frequent extreme events, and higher temperatures that reduce coffee quality (Schroth et al. 2009). Soto-Pinto et al. (2009) observed that in Chiapas, Mexico, the integration of timber trees into pasture land as part of a carbon project (Scolel'Te) created a strong incentive for not burning these pastures. Similarly, farmers practicing rubber agroforestry in the Tapajós region of Brazil have strong reasons to avoid the spreading of fire from their slash-and-burn plots (Schroth et al. 2003).

A study of the West Arnhem Fire Management Agreement in Australia, where the climate is predicted to become drier, found that the creation of fire breaks through early dry season prescribed fires reduced more dangerous wildfires by 15–20% across 28,000 km^2 and could reduce the yearly emissions associated with those wildfires by 100,000 Mg CO_2 (ProAct 2008). The same study also found that earlier dry season fires emit less GHG than later dry season fires because they are not as intense, burn less grassy fuel, do not burn the entire grass layer, stay in the grass layer without invading the canopy, and can be stopped more easily. Fire management implemented in that project had the added benefit of increasing aboriginal community participation, enhancing cultural practices around fire and providing payments to the Aboriginal Traditional Owners of Western Arnhem Land of $1 million per year over 17 years for the offset of 100,000 Mg CO_2 each year.

Windbreaks

Principle: Windbreaks sequester carbon and protect against erosion from wind and floods.

Shelterbelts, greenbelts, hedges, and living fences serve as windbreaks and shade the soil, binding it together with roots, trapping water, and restoring soil organic matter content. The amounts of carbon sequestered in these systems can be quite substantial with values in the range of 20–36 Mg C ha^{-1} in plant biomass and a potential 10% per hectare increase in soil organic carbon (Albrecht and Kandji 2003). All these techniques increase resilience to drought as well as improve soil health and prevent erosion through protecting fields from wind and surface water flow while often providing biodiversity benefits (Klein et al. 2007; ProAct 2008). The many benefits of windbreaks can be seen in a government adaptation project in Niayes region of Senegal promoting irrigated farming that also involved the planting of windbreaks along roads. The windbreaks increased agricultural productivity, reduced soil erosion and desiccation, and provided fuelwood for cooking, which had the added benefit of decreasing the need for women and girls to travel long distances in search of wood. The windbreaks also sequestered carbon (Klein et al. 2007). Another project in Sudan—the "Community-Based Rangeland Rehabilitation for Carbon Sequestration Project"—restored 700 ha of community rangeland by planting grasses and leguminous crops. The project also protected more than 300 farms from wind erosion by planting *Acacia senegal* and *Ziziphus mauritania* trees as windbreaks over 108 km.

The project aims to encourage community adoption of agroforestry through paying local communities for carbon offsets (Jindal et al. 2008).

Forest and Riverine Corridors

Principle: Forest and riverine corridors benefit adaptation by providing migration routes for animals and plants while storing carbon.

The restoration and conservation of forest corridors to improve forest connectivity is another mitigation activity that has adaptive benefits for both animals and people. Migration corridors can help species to shift their geographic distributions in response to a changing climate (Hannah et al. 2008; Heller and Zavaleta 2008) and can contribute to providing the genetic diversity necessary for adaptation as individuals move between populations, bringing alleles from one region that may not be present in another region (Guariguata et al. 2008). Forest corridors can also generate direct benefits to humans while at the same time sequestering carbon in tree biomass and soil. Examples include the protection against landslides and water conservation, as discussed previously, and may benefit agricultural systems by supporting pollination and pest control through protecting the habitats of the species that are involved in these processes (Scherr and Sthapit 2009).

The restoration and conservation of riverine corridors provides direct benefits to human adaptation by keeping water temperatures low in the face of temperature increases, thereby potentially protecting freshwater fisheries, while filtering nutrients from runoff and soil water (FAO 2008). Removal of riparian corridors, on the other hand, leads to higher daily and mean temperatures and results in faster nighttime cooling (Pyke and Andelman 2007) while reducing carbon storage. Riparian corridors also stabilize stream banks and decrease the sediment loads of streams, thereby reducing the negative effects of sediment deposition on spawning grounds of fish and on reservoir capacity, the latter being particularly critical in drying climates (FAO 2008).

Mangroves

Principle: Mangroves sequester carbon and protect coastal areas against increasing flooding risks.

Reforestation and avoided deforestation of mangroves offers another important synergy between adaptation and mitigation, with relevance to millions of people living and practicing agriculture in coastal areas and river deltas, in addition to the inhabitants of coastal towns and cities. Mangroves benefit these people through increased protection of coastal areas to erosion and storm surges. In addition, mangroves increase fisheries habitat, providing a direct source of food and income to local communities. Mangroves not only store carbon but may also serve as a complement and more cost-effective means of storm protection to built infrastructure.

For example, while storm damage to a sea wall would require costly repair, mangroves will naturally regenerate, although the level of protection and regeneration rate depends on area geomorphology, vegetative structure, and the frequency and intensity of storms (ProAct 2008).

There is evidence that many types of coastal forests can help dissipate wave energy and force, reducing flooding, and also help to capture debris that would otherwise do more damage (ProAct 2008). Recommended greenbelt width for protective mangroves varies from 100 m for tsunami protection in the Asia South Pacific to 200 m for protection of agricultural land (ProAct 2008), suggesting that carbon sequestration potential may be significant. However, given the lack of consensus on the capacity of mangroves to attenuate long-period waves such as storm surges and tsunamis (Mukherjee et al. 2010), they should not be seen as a substitute for early warning systems and planning for such events, but rather as part of a broader system of risk management (Baird 2006).

As with protection functions provided by other forms of forest, mangroves require time to mature before they offer their full protective benefit (ProAct 2008). Thus, avoided deforestation can be more effective as an adaptation strategy where existing mangrove structures are already meeting coastal protection objectives, as well as being more cost-effective than reforestation (UNEP RISOE 2010). In areas where people are heavily reliant on mangrove forests, the risk of mangrove loss can be minimized by increasing the capacity of communities to undertake alternative livelihood options (ProAct 2008).

Wetland Conservation and Restoration

Principle: Wetlands store carbon and improve water security by filtering pollution and managing water flow.

Wetlands in mountain areas supply water for agricultural land downstream while sequestering carbon. Natural peat wetlands in coastal and river areas serve as aquifers by absorbing and storing water in wet periods and releasing it slowly during low rainfall (FAO 2008). Wetlands discharge water through evapotranspiration, seepage, pipe flow from subsurface erosion, overland flow, and open channel flow (FAO 2008). In addition to managing water flow, wetland ecosystems, such as floodplains, salt marshes, mudflats, reefs, and wooded riparian zones can all serve as flood management protecting people, agricultural land, and infrastructure downstream (ProAct 2008).

Wetlands also filter pollutants such as arsenic, boron, mercury, nitrogen, and selenium out of water, making them possible candidates for water quality credits (Nyman 2011). Wetlands protect offshore fisheries from land-based pollution (FAO 2008), thereby potentially reducing the impacts of climate change on coastal fisheries. Wetlands are also gaining recognition for their carbon sequestration potential. Inland waters are estimated to transport and store approximately 2.7 Pg C year^{-1} (Battin et al. 2009). Wetlands store carbon with greater permanence than do oceans due to bottom-water anoxia in inland waters (Battin et al. 2009).

Trade-Offs Between Climate Change Adaptation and Mitigation

While there is a strong potential for synergies between adaptation and mitigation, in certain cases, there may also be trade-offs. The most common trade-offs are likely to occur where immediate infrastructure, water, and food security needs are satisfied at the expense of protecting ecosystems, thereby reducing their carbon stocks and jeopardizing the long-term flow of ecosystem services that would help to satisfy those needs over the longer term (Foley et al. 2005). Some examples of this situation follow.

Mitigation Activities: A Threat to Food Security?

The rising demand for cheap and abundant food, corresponding to the rapidly growing global population, has led to increased support for intensive agriculture. There is concern in some quarters that a shift away from intensive agriculture, through emphasizing reduced use of fertilizer and machinery and incorporating perennials to increase above and belowground carbon stocks, could threaten food security and farmers' livelihoods by reducing yields, which may already be under pressure from climate change (Smith 2009; Scherr and Sthapit 2009). Such concerns must be taken seriously and carbon sequestration or reduced emissions measures be introduced in agriculture only after careful evaluation of the consequences, rather than recommending "one size fits all" approaches.

The importance of highly participatory, site-specific approaches to promoting the inclusion of trees in agricultural systems or other "climate-smart" land-use practices cannot be overemphasized. Farmers are unlikely to adopt practices that they believe may compromise their crop yields or complicate their farming operations. For example, coffee farmers in the Sierra Madre de Chiapas, Mexico, who participated in a carbon payments scheme, rarely opted for the inclusion of additional trees in their already quite densely shaded coffee plots, which they rightly feared might have reduced coffee yields and increased disease pressures. However, many farmers had plots of annual crops or pasture, and so live fences to surround and subdivide these were perceived as the option for increasing the carbon stocks of their farms that was most compatible with their production objectives and was most commonly chosen (Schroth et al. 2011). Reforestation of sites that had been affected by wildfires or landslides was another option for increasing landscape carbon stocks without negatively affecting agricultural output (Schroth et al. 2009).

In addition, reforestation projects targeting presently underused land might conflict with future shifts in agricultural or pasture uses driven by climate change. Therefore, identification of land for reforestation and afforestation should consider future scenarios of land-use shifts, including through using agroforestry models that are more flexible to the integration of other land uses, such as crops and livestock, than are classical plantation forests. Again, participatory models that leave farmers a maximum of flexibility in how to achieve certain targets (e.g., an increment in farm carbon stocks) are among the best ways to increase adoption and permanence of proposed changes in agricultural practices (Schroth et al. 2011).

Tree Planting Versus Water Security

In regions with adequate water availability, afforestation and reforestation are often beneficial and can even increase water availability during the dry season by ensuring more gradual release of water from catchments. However, afforestation can also decrease water availability. Tree plantings use more water than other land uses, such as agriculture and pasture, and the removal of trees has been shown to increase downstream water yields (FAO 2008). One global study found reduced annual runoff levels of as much as 75% when grasslands were converted into *Eucalyptus* plantations (Jindal et al. 2008). Therefore, tree planting for climate change mitigation may have adverse adaptation effects in dry climates. Deciduous indigenous trees that shed their leaves in the dry season are often a more appropriate plantation choice in water-scarce catchments (Jindal et al. 2008).

In areas of low and decreasing rainfall, aboveground carbon stocks decrease when trees are removed to increase water yields from catchments, as has been the case in government campaigns to remove invasive trees from watersheds in South Africa. However, the net carbon release of such measures depends on the subsequent use of the tree biomass, with highest emissions occurring if trees are burned or left to decompose in the field, and less immediate and lower emissions if the timber is used for long-lived products (e.g., buildings) and eventually burned for generating energy and replacing fossil fuel. By reducing evapotranspiration, harvesting or removal of trees can increase groundwater levels. This is often desirable but may lead to increased salinization in areas where salt is present in the subsoil and is then able to move into the rooting zone of plants (Nuberg et al. 2009), hence the need to design site-specific land use solutions for both adaptation and mitigation projects.

Fast-Growing Tree Monocultures and Availability of Forest Resources

As discussed, the objective of maximizing tree growth in carbon sequestration projects should be balanced with the objectives of conserving and increasing the availability of native forest resources, such as wood, fodder, and various types of food, which may increase the resilience of local communities to climate change, as well as conserve local biodiversity. Therefore, the use of diverse stands of native trees is generally preferable to monocultures of exotic species (Brockerhoff et al. 2008).

Conclusions

Given the multiple mutual benefits between climate change adaptation and mitigation that this review has highlighted, we conclude that climate change adaptation should be integrated into mitigation projects wherever possible, while adaptation projects should preferably include mitigation components. The potential for the integration of mitigation objectives is particularly high in ecosystem-based adaptation approaches that have been highlighted in this chapter. In places where adaptation is needed and there is a risk of trade-offs with mitigation, adaptation should be prioritized as the more site-specific need, while mitigation projects have a global impact and are therefore geographically more flexible. In such instances, research into adaptive strategies that minimize damage to ecosystems and aid in mitigation should be prioritized.

Emission reductions achieved through integrated adaptation and mitigation activities should be promoted in the voluntary and compliance carbon markets, while adaptation projects should be designed with the objective of, as a minimum, no increase in carbon emissions. Emission reductions from sequestration through agricultural activity should be treated as equivalent to other offsets and should not be relegated to the lower tier of temporary certified emissions reductions (tCERs), as is currently the case with agricultural mitigation efforts. One way to address the concern about the permanence of carbon sequestration benefits obtained through agriculture for carbon markets is to include education campaigns, incentives such as long-term payments or tax rebates for carbon storage and "climate-smart" agricultural practices, and other adaptation-style strategies into mitigation projects. This is necessary to ensure that carbon sequestered in agricultural systems remains in place for periods long enough to have a significant climate benefit.

Many of the most promising techniques that combine adaptation and mitigation, such as those that combine trees in cropping systems or trees with animal production, are very knowledge intensive. This means that smallholders must over time learn a suite of new methods and gradually and successfully integrate them into their production systems. A significant level of support and knowledge transfer is required for this process to be attractive, successful, and of low risk to the participants, and subsidies, for example, through payments for carbon conservation or other environmental services, may be necessary to increase adoption rates of such practices. Overall, forestry and agroforestry projects involving the local community in management have lower-risk profiles than large plantations. As the investment in efforts to build climate-resilient development outcomes increases through dedicated (but "project-based") adaptation funding mechanisms, the opportunities for revenues from REDD+ projects to offer financing for community-level adaptation initiatives need to be explored.

In summary, given the severity of anticipated climate change, a rapid and truly integrative response is required on the part of the global community. The most efficient use of limited resources needs to be attained. Where efforts at climate change adaptation and mitigation can be combined so that resources do double-duty, this should be done. In other cases, government planners and project developers should avoid trade-offs where efforts in one sphere compromise the other. Opportunities for synergy between climate change adaptation and mitigation can be further developed by increasing the understanding of the complex interactions within natural and human-managed systems.

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