Advanced Review

Forests and trees for social adaptation to climate variability and change

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Ecosystems provide important services that can help people adapt to climate variability and change. Recognizing this role of ecosystems, several international and nongovernmental organizations have promoted an ecosystem-based approach to adaptation. We review the scientific literature related to ecosystem-based adaptation (EBA) with forests and trees, and highlight five cases in which forests and trees can support adaptation: (1) forests and trees providing goods to local communities facing climatic threats; (2) trees in agricultural fields regulating water, soil, and microclimate for more resilient production; (3) forested watersheds regulating water and protecting soils for reduced climate impacts; (4) forests protecting coastal areas from climate-related threats; and (5) urban forests and trees regulating temperature and water for resilient cities. The literature provides evidence that EBA with forests and trees can reduce social vulnerability to climate hazards; however, uncertainties and knowledge gaps remain, particularly for regulating services in watersheds and coastal areas. Few studies have been undertaken on EBA specifically, but the abundant literature on ecosystem services can be used to fill knowledge gaps. Many studies assess the multiple benefits of ecosystems for human adaptation or well-being, but also recognize trade-offs between ecosystem services. Better understanding is needed of the efficiency, costs, and benefits, and trade-offs of EBA with forests and trees. Pilot projects under implementation could serve as learning sites and existing information could be systematized and revisited with a climate change adaptation lens.

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INTRODUCTION

Climate change will affect human well-being in many parts of the world[1] and effective adaptation is needed even under the most stringent mitigation scenarios.[2] The role of ecosystem goods and services in societal adaptation to climate variability and change has received renewed recognition. Ecosystem-based adaptation (EBA) is an anthropocentric approach, in which ecosystem services are conserved or restored to reduce the vulnerability of people facing climate change threats.[3,4] Ecosystem services are the benefits people obtain from ecosystems and can be classified as provisioning services (e.g., timber and firewood), regulating services (e.g., water regulation), and cultural services (e.g., recreation).[5] Examples of EBA include the restoration of mangrove shelterbelts for the protection of coastal settlements against storms and waves and the conservation of forested watersheds for the reduction of flood risk.

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Many international and nongovernmental conservation and development organizations have promoted EBA by stressing its effectiveness in reducing social vulnerability, its cost-efficiency, and its co-benefits for biodiversity conservation, poverty reduction, and climate change mitigation.[6–12] However, the evidence on EBA effectiveness needs to be strengthened,[13] particularly as pilot projects are being implemented, for example in Colombia, Tanzania, and Sri Lanka.[9]

As a first step in addressing this need, we present peer-reviewed scientific literature related to the role of forest and tree ecosystem services in reducing social vulnerability to climate variability and change. This literature is grouped into five 'cases'. For each case, we describe the findings and evidence from papers dealing explicitly with the three following elements: climate variability or change, social vulnerability, and forest or tree ecosystem services. We then discuss uncertainties, controversies, and trade-offs using broader literature.

CASE 1: FORESTS AND TREES PROVIDING GOODS TO LOCAL COMMUNITIES FACING CLIMATIC THREATS

Forest and tree products, such as timber and non-timber forest products (NTFPs; for example charcoal, firewood, wild fruits, mushrooms, roots, and fodder) constitute important safety nets and are part of income diversification strategies for many communities in developing countries facing increased climate variability and climate hazard risks.

Rural communities use forest products as part of their coping strategies (i.e., in reaction to stresses) when crops fail due to drought. During and after the dry spells of 2005–2006 in the semiarid areas of Tanzania, households consumed forest products directly as part of their food intake, and earned 42% of their total income from selling wild fruits, firewood, timber, and charcoal.[14] In rural areas of Peru, the gathering of forest fruits, palm hearts, and other products is an important strategy for coping with floods.[15] Forest products also play a part in post-disaster strategies in Honduras: rural households sold timber and other products to recover from land losses during Hurricane Mitch.[16]

Many agrarian communities also use forest and tree products for income diversification as an adaptive strategy (i.e., in anticipation of stresses). Livelihood diversification is the main strategy for dealing with climate variability in Tanzania, and is partly achieved with the collection of firewood, fruits, spices, fodder, traditional medicines, and meat, and the production of timber, charcoal, and bricks.[17] In some of the studied areas in Tanzania, up to 68% of household income comes from forests. Rural communities of the Congo Basin use forests extensively for subsistence and livelihoods and also to cope with climate variability related to the start and duration of the rainy season.[18–20] Sustainable forest management by hillside communities has enhanced local livelihoods in Bolivia, through the provision of timber and NTFPs, and has increased their resilience to drought and irregular rainfall.[21]

West African farmers have long been managing trees to reduce their sensitivity to climate variability through a continuous harvest of products. This includes fodder for livestock during the dry season or firewood, fruit, and medicinal products consumed or sold, e.g., in Niger,[22,23] Mali,[24] or Burkina Faso.[25] In Rajasthan, India, farmers commonly sell fodder from *Prosopis cineraria* and *Ziziphus nummularia* (trees maintained on croplands) for a higher price during drought years to make up for income lost from crops.[26] The mango-based multi-storey cropping systems of the Padma floodplain in Bangladesh were found to increase farmer resilience to climate-related and other shocks by providing diverse products all year round (e.g., mango fruit, timber, bark and leaves, and wheat, sugarcane, papaya, banana, ginger, turmeric, and various species of vegetable).[27] Although dense shade trees such as shea butter (*Vitellaria paradoxa*) and néré (*Parkia biglobosa*) can reduce millet yields, they are valued by farmers in West Africa, because the value of tree products compensates for crop yield losses, especially during dry spells.[28] Similarly, in semiarid Kenya, the fast-growing indigenous *Melia volkensii* provides high value timber and a range of goods under drought conditions.[28]

Many studies report that the poorest households rely more on forest products for their coping and adaptation strategies. For example, during flood in Pacaya-Samiria, Peru, the young and poor households without upland access or rich fish stocks nearby turned to NTFP gathering.[15] Low-income households turned to forests in times of misfortune because harvesting, especially of NTFPs, usually requires limited financial, physical, or human capital and is possible under local tenure systems. Research in two villages in Eastern Cape and Limpopo provinces, South Africa, revealed that 70% of households used NTFPs to help cope with shocks, including climatic ones, and poorer households relied more on the use or sale of NTFPs.[29] In southern Malawi, households with the lowest income, or headed by older and less-educated individuals, depended the most on the forests for their coping strategies during drought.[30] People without agricultural assets relied heavily on forests after a disaster in Honduras.[16] Similarly, in Indonesia, the most heavily affected, the poorest and the least-educated relied more on forests for their coping strategies after a flood.[31]

Several studies link exclusion from forest resources to vulnerability. Temperature increases and irregular rainfall in the Endau hilltop, Kenya, have led to decreased yields, crop failure, and water scarcity, severely impacting farmers and pastoralists without access to forest products such as wood, honey, herbs, bushmeat, and fodder.[32] In many coastal areas of South and South-east Asia, mangrove forest conversion or exclusion from access has increased the vulnerability of poor coastal communities. When mangroves are restored and accessible, people have access to diversified products (fish, firewood, timber, construction material, fodder, medicinal plants, and honey) and are more resilient to climate hazards, as was shown in Vietnam,[33–35] Bangladesh,[36] and the Philippines.[37]

Most case studies provide clear evidence from field surveys and household interviews to demonstrate the importance of forest and tree products for both the short-term coping strategies of poor local communities and the longer-term diversification of livelihoods under climate variability and change.

The case studies differentiate between forests as safety nets for coping strategies and forests as a major source of livelihood diversification for adaptation strategies. It is, however, difficult to position certain strategies on the continuum between coping and adapting. Many households utilize forest goods as part of their daily livelihoods, which in turn decreases their sensitivity to climate, because the diversified products are not affected in the same way or at the same time by climate events.[38] These households also modify their use of forest products to cope with specific events.

One difference between coping and adapting lies in anticipatory action—for example, the management or restoration of forests for ensuring the future provision of products. In this context, governance is key to understanding why some ecosystems are used as safety nets, without much investment in management, and others are managed to ensure sustainable and resilient livelihoods. Well-defined property rights and access are critical components of local management systems.[39,40] Collective or individual property rights offer incentives to maintain the resource stock over time and reduce the vulnerability of those depending on it.[41] Many authors have demonstrated the correlation between these rights and positive livelihood outcomes (e.g., economic opportunities, food security and social capital), as well as better ecological forest conditions.[42–44] Conversely, introducing trees on agricultural lands is sometimes used as a strategy to secure property rights that are transferable to future generations.[27]

A high dependence on forest products for dealing with climate events can be a source of vulnerability when the ecosystem is degraded or mismanaged, when conflicts arise between different forest users, or when access becomes restricted. However, situations of open access are not desirable either, as they can lead to the degradation of resources with consequences for users.[43] If climate stresses increase with climate change, the intensive resource extraction that can occur after repeated climate events can lead to a scarcity of forest goods[17,30] and make the use of forest products unsustainable. Thus, governance systems must deal with the trade-offs between providing products for current stresses and managing ecosystems for the future. Governance will determine how coping strategies using forest products can be transformed into sustainable adaptive strategies, ensuring livelihood security under climate change.

In several case studies, the role of forest products is not limited to local consumption for food security, but includes commercial activities. Increasing market access might offer diversification opportunities for products that are traditionally produced for subsistence alone, with positive outcomes for livelihood and social resilience.[23] However, market access can also lead to intensive exploitation and resource-decline, particularly for high-value and high-demand products.[45] Price fluctuations can create additional vulnerabilities, especially for specialized communities or households.[46] Market-based strategies should be treated cautiously because external interests or local elites can capture a disproportionate share of the benefits from the sale of NTFPs once their value is recognized or once infrastructure development facilitates traders' access to previously remote communities.[46]

Several case studies show that the poorest often rely the most on forest products for their coping and adapting strategies. Pattanayak and Sills[47] explained this reliance on forests as resulting from a lack of alternative strategies (e.g., working off-farm, creating buffer stocks, or cultivating different fields) rather than poverty. Levang et al.[48] also recognize the importance of forest products as safety nets when no alternatives are available. But relying on natural resources as a safety net can be a poverty trap, particularly when resource availability is low, the population in need of safety nets is large, and alternatives are lacking.[49] Adaptation policies or projects focusing only on the conservation of forest resources could be counterproductive and should rather develop diversification strategies in complement to sustainable forest management. Thus, forests and their safety nets become part of a portfolio of adaptation activities.

CASE 2: TREES IN AGRICULTURAL FIELDS REGULATING WATER, SOIL, AND MICROCLIMATE FOR MORE RESILIENT PRODUCTION

Smallholder farmers and agriculture are threatened by rainfall and temperature variability. Trees in agricultural fields can help maintain production under a variable climate and also protect crops against climate extremes.

Agroforestry (combining trees and shrubs with crops and/or livestock) is increasingly recognized as an effective approach for minimizing production risks under climate variability and change.[28] With their deep root systems, trees are able to explore larger soil depths for water and nutrients, which will be beneficial to crops in times of drought. Their contribution to increased soil porosity, reduced runoff, and increased soil cover leads to increased water infiltration and retention, and reduction of moisture-stress during low rainfall. On the other hand, excess water is pumped out of the soil more rapidly in agroforestry plots due to their higher evapotranspiration rates.[28]

Research in Africa shows that nitrogen-fixing trees make agriculture more drought-resilient due to improvements in soil nutrients and water infiltration, especially in degraded land. In Malawi and Zambia, maize production yields are greater where conservation farming is practiced with *Faidherbia albida*, a tree shedding its foliage during the early rainy season when crops are established and re-growing its leaves at the end of the wet season, thus limiting competition for light, nutrients, or water with growing crops.[22] In Malawi, farmers practicing agroforestry with *Faidherbia* and *Gliricidia* obtained at least modest yields during drought seasons, while farmers not using these practices experienced crop failure.[22] Farmers in the Farmer Managed Natural Regeneration (FMNR) programme in Niger claim that trees such as *Faidherbia* improve their sorghum and millet yields, in part due to reduced wind speed and increased soil moisture.[22,23] Recent droughts had less negative impacts on the FMNR areas than on other regions.[50]

Nitrogen-fixing species are used extensively by communities in the drought-prone regions of Rajasthan, India, to help secure grain production under inadequate rainfall.[26] In eastern and southern Africa, nitrogen-fixing trees are also used in fallows to restore soil fertility and water holding capacity, which enhances maize yields in dry years.[28] The benefits of agroforestry systems can be significantly enhanced through traditional soil and water conservation techniques, as seen in Burkina Faso, where farmers practicing such techniques (e.g., stone dykes and soil pits filled with organic matter) were found more likely to regenerate and protect trees in their fields.[25] Trees can also be used in irrigated areas—e.g., in the Senegal River basin, agroforestry (e.g., millet with *Faidherbia albida*) could be applied where rice cultivation is not sustainable because of water scarcity. The trees protect irrigated plots from wind and water erosion, they regulate microclimate by decreasing insolation and evapotranspiration, and the agroforestry system needs less water than rice.[51]

Trees can be beneficial for cash crops such as coffee and cacao as well. Coffee is sensitive to microclimate fluctuations—e.g., the optimal temperature range for Arabica coffee is 18–21°C.[52] Shade trees control temperature and humidity fluctuations and can also provide protection from wind and storm events that defoliate coffee trees.[53] Research in coffee systems In Chiapas, Mexico, showed that shade decreases temperature and humidity fluctuations and reduces vulnerability to water stresses.[54] In Sulawesi, Indonesia, a study showed that cacao systems shaded by *Gliricidia* trees are not significantly affected by drought because of shade and water uptake from the trees.[55]

The reviewed studies show that trees have the potential to improve soil fertility, soil moisture, and microclimate in agriculture and make crop production more resilient to climate variability. The studies provide evidence from biophysical field measurements, agronomic surveys, and yield measurements in different agricultural systems during rainy seasons and dry spells. The degree of effectiveness of trees in sustaining agricultural production, however, varies across regions and crop types due to differences in soil properties, rainfall, and other characteristics.[22]

Trade-offs occur between the different effects of trees on agriculture—e.g., dense tree cover protects soils, but competes with crops for light. Because of the diverse interactions between trees and crops, it is difficult to be conclusive about the relationship between shade cover and yield. The position of the trade-off point, where the positive effects of shade cover are maximized, is context-specific.[53] Other trade-offs occur with regards to crop yields versus resilience, as trees can buffer crops against climate events, but decrease average yields in the absence of climatic and other disturbances. In a context of climate change, questions remain about what agroforestry systems are needed for resilience under different climate scenarios and production demands.[28] Nevertheless, the value of trees for agriculture is high in environments characterized by high climatic risk (e.g., in drylands) and areas with low soil fertility and agricultural inputs (i.e., where chemical fertilizers or irrigation cannot buffer soil degradation and climatic events).[22,23,26]

The benefits of agroforestry are well studied, but rarely from the perspective of buffering production against climate variability. Scientists have just begun looking at ongoing trials and re-analyzing results to see what can be learned about the performance of different systems in exceptional years.[28] Multidisciplinary research is scarce on the combined ecological and socioeconomic trade-offs of agroforestry,[56] and more so from a climate variability or change perspective. In most cases, the resilience of farming systems is influenced by both tree products (Case 1 of this paper) and services (this case), and the analysis of different tree species or management options must combine both aspects.

Despite the demonstrated benefits of agroforestry systems, their expansion has been constrained. Governments in many tropical countries have been promoting agricultural intensification as a replacement for agroecological and swidden systems, with the assumption that it would enhance food security, increase farmer income, and protect forests.[53,57] However, intensification can exacerbate vulnerability to climate change[54] and lead to deforestation.[58] Other approaches have been proposed in which agricultural intensification occurs in association with trees, with the objective of conserving ecosystem services and increasing farmers' income.[56] This relates to the debate on land sparing (where agricultural production is maximized in some areas of a landscape and natural ecosystems conserved elsewhere) versus land sharing (where conservation and production are integrated in heterogeneous landscapes). The land-sparing approach emphasizes landscape optimization, whereas land-sharing focuses on coupled human–ecological systems. Deciding which approach is appropriate depends on the social and biophysical context.[59] Overall, ensuring food security in a changing climate will require adaptation at all levels, from the production, distribution, and allocation systems, to the enabling local, regional, and global institutions.[60]

Agroforestry for increased resilience to climate variability works when it is low cost and flexible enough for communities to test it, learn from each other, and spread innovations—as in the case of FMNR.[23,61] Policy, incentives, and institutions supporting agroforestry are also crucial for the adoption of agroforestry practices.[62] For example, certification schemes and premiums on shade-grown coffee and cacao, or payments for ecosystem services can foster the adoption of agroforestry schemes.[63] However, some markets and subsidies place agroforestry at a disadvantage by overly supporting agricultural intensification and biofuel and wood plantations.[64] Subsidies can be used creatively to promote tree-based systems—e.g., by linking fertilizer subsidies to agroforestry investments on the farm with nitrogen-fixing trees, as proposed by Garrity et al.[22]

Other factors influence adoption, such as household characteristics (e.g., gender), the intervention of extension services, tenure systems, and the pressure on land and forest resources.[63] Secure rights to both land and products are crucial for the adoption and enhancement of agroforestry.[63,65] In the case of FMNR in Niger, the change process began with governance, followed by economic and ecological changes that reinforced governance changes.[50] Initial tree tenure offered no real incentive for people to protect trees because the government owned all trees.[23] The FMNR project worked with local forestry authorities to ensure that people would benefit from protecting the trees and people were ultimately allowed to make their own decisions about when and how to use them. Empowering peasant farmers as active agents of change stimulates action and long-term adaptability.[66] Action for agroforestry, however, should first focus on getting the supportive institutional arrangements in place (rules, organizations, and incentives).[62]

CASE 3: FORESTED WATERSHEDS REGULATING WATER AND PROTECTING SOILS FOR REDUCED CLIMATE IMPACTS

Forests influence rainfall interception, evapotranspiration, water infiltration, and groundwater recharge. They contribute to regulating base flows during dry seasons and peak flows during rainfall events, both of which are services of utmost importance for the adaptation of people to climate variability and change. They also stabilize soil and prevent erosion and landslides, reducing further the negative impacts of these hazards (partially climate-related) on infrastructure, settlements, and water users.

In Flores, Indonesia, tropical forested watersheds have been shown to increase base flow (i.e., the proportion of stream flow coming from groundwater in the absence of rainfall) and reduce the impacts of drought on downstream agrarian communities.[67] Under irregular rainfall, agricultural households in the proximity of forested watersheds have higher profits than other households.

A forest regeneration and plantation forestation project in Bolivia has been shown to reduce the vulnerability of the Khuluyo communities to both irregular rainfall and more intense storms.[21] The local communities depend on irrigation for their agriculture and frequent storms cause soil erosion and landslides. The promotion of natural forest regeneration has improved water provision during the extended dry periods. Natural regeneration and forest plantations have also stabilized hillsides and thereby reduced the vulnerability of settlements and agricultural land to soil erosion and landslides.

The root causes of the 1988 landslides in Thailand were linked to unprecedented heavy rainfall and slope geomorphology, but also to deforestation and forest conversion.[68] The mountainous headwaters were once entirely forested, but agricultural encroachment and deforestation cleared much of the forest, replacing it with rubber plantations in many locations. While rubber plantations are an important source of income for many communities, their shallow roots are not efficient in holding the soil together.

In the Philippines, the loss of lives and widespread economic damage due to tropical cyclones in 2004 were attributed to deforestation among other factors.[69] The heavy rains caused landslides and debris flows from mountainous areas, and also river overflows, dam breaks, and flooding. Impacts were exacerbated by the lack of forests on the slopes and watersheds to retain the soil and reduce peak flood flows. Flooding in low lying areas of Cameroon was also attributed to land-use change.[18]

Evidence is scarce on the role of watershed regulating services for social adaptation to climate variability and change, even though there is abundant literature on the relationship between forests and water that could inform decisions on EBA. Among the reviewed articles, only one explores the hydrological role of forests in relation to a climate hazard and uses hydrological modeling with data on water flows, precipitation, topography, vegetation, and soils.[67]

Studies on EBA or proposed measures should not be based on conventional beliefs—e.g., the belief that natural and planted forests increase total water flow, which contradicts numerous studies of small paired watersheds showing the opposite is true.[70] Several authors have analyzed conventional beliefs and compared them to scientific evidence.[71–74] These beliefs are deeply rooted in public perception—e.g., in Central America, more than 90% of survey participants perceived that forests increase total water flows.[75]

The influence of forests on storm flow and floods is highly debated. Even if forests tend to increase infiltration and evapotranspiration and may reduce storm flow, evidence on the reduction of floods by forests is questioned.[76] According to Bruijnzeel,[72] large rainfall events are not regulated by forests when soils are wet. However, studies of paired watersheds may be biased because they do not take into account the frequency of floods.[77] Forest cover has been shown to reduce this frequency.[78] Hydrologic research on forest and flood links needs to be revisited and increased,[79] especially because some watershed management plans are based on forest and tree management. For example, tree planting was proposed after hurricane Mitch in Central America for protecting watersheds during extreme climatic events, without much evidence about expected outcomes.[74] However, even though the role of forests in preventing large-scale floods is controversial, their role in preventing average and most frequent floods should not be overlooked.[70]

The effect of forests on base flow cannot be generalized because it results from two competing processes: forests generally present higher transpiration (thus a lower base flow) and higher infiltration (thus higher soil water recharge and higher base flow) than non-forest land uses.[72] If forests increase water infiltration in soils more than they increase transpiration compared to other uses, they contribute to conserving base flows. This shows the importance of considering soil properties and management when comparing forest and non-forest land uses.[79]

The issue of scale is crucial for determining the effects of forests on water.[80] For instance, the effects of forests on reduced storm flows or total annual flows are clearer in small watersheds than in large watersheds.[70] At the regional scale, other processes have to be considered besides infiltration, runoff and evapotranspiration (the latter being considered as a loss of water for human uses, when a local or watershed perspective is adopted). At the regional and global scale, forests play a role in recycling rainfall and generating flows of atmospheric water vapor, but this role is not well quantified. Although evapotranspiration by forests reduces total water flows in a watershed, it also pumps water back into the atmosphere, which can increase rainfall in the region.[80] Forests may also act as a pump of atmospheric moisture, attracting moist air from oceans to inland regions,[81,82] but this role of forests in hydrological processes at the regional scale is debated.[83]

Regarding soil erosion and landslides, the literature confirms that surface erosion is generally low in forests compared to other land uses, because of the higher soil protection and the lower runoff under forests.[84] It is also generally observed that landslides occur less often in forested areas than in non-forested areas,[85,86] particularly because forests increase soil cohesion with their roots.[84] However, uncertainties remain about the role of forests in landslide prevention. For example, after the 1988 landslides in Thailand, some studies concluded that landslide occurrence was independent of vegetation cover and that rainfall intensity overwhelmed the role of roots in stabilizing soils.[84] Thus forests can reduce the effects of increased rainfall intensity on soil erosion, but may have a lesser role to play for disaster risk reduction.

Uncertainties and lack of context-specific data hinder the promotion of EBA measures in watersheds, but another major barrier is related to externalities. Most watershed management issues (either with a focus on climate-related stresses or not) face problems with externalities, as the decisions of stakeholders managing land and water upstream affect other stakeholders downstream. Watershed EBA should thus develop coordination mechanisms between water users and managers, as well as compensation mechanisms for distributing the costs of watershed management. For example, opportunity costs linked to forest conservation upstream can be compensated by payments for environmental services.[87]

CASE 4: FORESTS PROTECTING COASTAL AREAS FROM CLIMATE-RELATED THREATS

Coastal forests such as mangroves can protect coastal zones from tropical storms, sea-level rise, floods, and erosion due to their ability to absorb and dissipate wave energy and stabilize coastal land.

The storm protection services of mangroves became apparent in the aftermath of the 1999 cyclone in Orissa, India. Villages that were protected by mangroves suffered less losses of life, property, and crops.[88,89] The coastal communities of Nijhum Dwip Island in Bangladesh believe that the restored mangroves protect against natural disasters, in addition to providing raw materials and protecting soils.[36] In the Philippines, the population of Panay Island is willing to protect the mangrove ecosystem, as almost all believe that it provides storm protection services among other benefits.[37]

Coastal forests can be effective in controlling erosion as well. In Martinique, West Indies, where the majority of the beaches are at risk of erosion, an analysis of existing coastal management practices and mapping of current and projected vulnerability suggested protection and rehabilitation of mangrove forests as the priority adaptation strategy for 15% of Martinique's coastal zone.[90] An analysis of coastal zone changes in Zanzibar, Tanzania, in the past 50 years indicates that erosion and beach encroachment are correlated to the decrease in indigenous vegetation.[91] Coastal forests prevented excessive erosion by stabilizing beach sand, absorbing wave energy, and playing a role in beach development. This was also recognized by coastal zone communities and stakeholders who proposed planting of trees, shrubs, and creepers as a priority and 'no-regret' measure to deal with erosion.[91]

In Vietnam, economic valuations showed that planting mangroves on the seaward side of sea dykes reduced the costs of maintaining these defences, as mangroves dissipate destructive wave energy, stabilize the sea floor and its slope, and trap sediment.[33–35] The annual benefits of mangrove restoration for dyke protection were US $70–130/ha/year depending on the discount rate; the benefits from products were US $700–1700/ha/year; and the restoration costs US$170–310/ha/year. These benefits of mangrove restoration for dyke protection include only the reduction in maintenance costs and not the avoided damage.[92]

Different kinds of evidence are provided for this case, such as correlation models between mangrove cover and storm impacts,[88] simulation of the buffer role of mangroves,[35] and economic valuation.[33] Evidence is also derived from analyses of community perceptions.[36,37]

Despite the evidence provided, it is difficult to determine how much protection mangroves provide and what factors explain this protection.[93] Some scientists have criticized the fact that much of the evidence on the protective role of mangroves during extreme events remains anecdotal, descriptive, or theoretical, without adequately addressing possible confounding factors, such as topography, near-shore bathymetry, distance from the coast and human factors, such as emergency response measures.[94–97] It is thus of concern that adaptation efforts may be carried out in coastal regions without a good understanding of each particular area's coastal dynamics and mangrove protection.

It is still unclear how much mangrove forest is needed to reduce the vulnerability of a particular area and what ecosystem characteristics determine its protective role. The extent of mangrove forest required for coastal protection depends on geomorphology and the risk of extreme events.[95,98] Mangrove width is particularly important for explaining the protective role; however, the minimal mangrove width for a particular area will also depend on the mangrove structure.[99] Root systems and trunk diameters are important for normal wave attenuation, but it is the vertical configuration of mangroves that becomes more critical during storm events.[99] Species diversity can enhance protection, because the diversity of trunks and roots will create different levels of roughness.[98]

Species type and composition are also important for mangrove resilience to, and recovery from, disturbances such as extreme events, sea-level rise, and alterations in hydrological regimes.[98,100] The resilience of mangroves is crucial for the sustainability of their protective role, as these ecosystems are exposed to sea-level rise and climatic changes and can deteriorate into states where they can no longer provide services.[101,102] In many contexts, protecting existing coastal forest barriers is more sustainable than replanting new ones,[96] as altered conditions can make mangrove regeneration or restoration difficult.[103]

Coastal forests can provide some protection from storms and cyclones, but they should be considered as part of a broader adaptation and disaster risk reduction strategy, especially since they cannot guarantee full protection from extreme events.[93,104] There is, however, greater confidence in the ability of coastal forests to stabilize erosion due to sea-level rise and tidal flooding.

CASE 5: URBAN FORESTS AND TREES REGULATING TEMPERATURE AND WATER FOR RESILIENT CITIES

Urban forests and trees can provide shading, evaporative cooling, and rainwater interception, storage, and infiltration services in cities. They can play a significant role in urban adaptation to climate variability and change.

Owing to their altered surface covers, where built areas have replaced vegetation,[105] urban areas face increased rates and volume of surface runoff, and urban heat island (UHI) impacts. It has been shown that adding green cover in Manchester, UK, has the potential to reduce runoff during rainfall events.[105]

UHIs occur due to urban surfaces, such as concrete, brick, asphalt, and stone which absorb short-wave solar radiation and then re-radiate it as long-wave radiation. In New Jersey, USA, urban trees are shown to reduce the health impacts of UHIs (resulting from heat stress and air pollution), and also reduce energy consumption for air conditioning.[106] Large and mature trees tend to be particularly effective as they provide a greater canopy and shade area. Areas with mature tree canopies can be 2.7–3.3°C cooler than areas with no trees.[106]

Green cover appears to influence surface temperatures strongly in Manchester, UK. The maximum surface temperature of urban woodlands is 18.4°C, whereas it is 31.2°C in town centers with the least extensive tree cover. Adding 10% of green cover to town centers could decrease maximum surface temperatures by 2.2°C. By 2080s, projections indicate an increase in maximum surface temperatures of 1.5–3.2°C in woodlands and 2–4.3°C in town centers, depending on the emissions scenario.[105]

In Tahoua and Zinder, Niger, forests and trees were shown to minimize the adverse climate impacts in urban areas through the regulation of microclimate and storm water.[107] In another study, higher temperatures were observed in commercial and industrial areas of Enugu, Nigeria, than in areas with forests.[108]

The few studies on the role of forests and trees in urban adaptation to climate variability and change in developed countries are well substantiated, with modeling based on aerial photographs and remote sensing, land-use and climatic data, and hydraulic and energy-exchange models. However, research on this subject in developing countries is still in its infancy, hence evidence remains limited.[109] Similarly, studies on urban ecosystem services in general have also mostly focused on developed countries.[110] The rapid growth of cities in many developing countries calls for the consideration of climate change adaptation in urban land-use planning and an evaluation of the benefits of ecosystems. This must take into account particular adaptation challenges related to the lack of 'grey' infrastructure (e.g., drains), large-scale destruction of 'green' infrastructure (e.g., wetlands) and capacity issues linked to poverty, poor local governance, and large concentrations of people in high-risk areas such as slums.[107,111]

Trees are generally a better option than grasslands for cooling and reducing runoff because they are less sensitive to drought. However, they cannot act as a standalone solution against flood impacts, and other measures might be needed such as green roofs.[105] Proposed EBA for cities deals mostly with the development of urban trees and parks to reduce UHIs or floods. For example, a 50% increase in tree cover is proposed for Enugu, Nigeria as a way to reduce UHIs.[108] However, EBA for cities should also consider other scales and include forest management outside the urban areas, in watersheds

(Case 3) and coastal areas (Case 4). Ecosystem services from surrounding rural areas can significantly affect urban well-being, indicating the need to think in terms of broader rural–urban landscape systems.[112] Ecological networks could enhance the overall benefits of EBA in cities. In Beijing for example, a green system is proposed at three levels: regional (natural and semi-natural forest areas and buffer belts), city (parks and green corridors), and neighborhoods (green extensions, road and vertical greening).[113]

The introduction of EBA measures within cities raises concerns about trade-offs related to the management of trees and forests. Urban green spaces can divert natural resources from other uses: e.g., water may be needed to maintain trees at the detriment of other users during water rationing in times of drought.[105] Other major concerns are related to opportunity costs, because of the forgone economic benefits of urban expansion.[114] The costs associated with urban forests have generally been neglected in both science and urban planning.[115] Many projected tree plantations in optimum scenarios of urban land-use planning are on private property, incurring costs to the owners.[106] The less-affluent inner-city neighborhoods have little open space available and limited funds for tree planting.

Experience with Durban's Municipal Climate Protection Programme indicates that achieving EBA in cities entails moving beyond the uniform, one-size-fits-all solution of street trees and parks to a deeper understanding of ecosystem ecology and resilience, and the potential of 'bio-infrastructure' to improve the well-being of vulnerable communities on multiple levels.[111] Durban's early experience shows that while EBA may have multiple, long-term benefits, these can only be realized if a number of preconditions are met, such as the development of structured and resourced programmes that have direct and immediate development co-benefits for local communities. All local governments should endorse EBA, as cities are affected by decisions and management in upstream and surrounding municipalities. Unfortunately, however, decisions are often made based on single management objectives, which can lead to conflicts among different groups of urban stakeholders.[115]

DISCUSSION

Substantial evidence exists that forest and tree ecosystems can reduce social vulnerability to climate variability and change. In Case 1, forests provide important safety nets, livelihood diversification, and integral income sources for many rural communities, making forest and tree products relevant for the adaptation of these groups. However, the sustainability of forest-based strategies is questionable in situations where products are used for coping with short-term shocks, without long-term objectives for managing forests and trees. Another issue is that forest products are often used by the poorest because they do not have alternatives, meaning that an adaptation strategy based on products alone can be a poverty trap.

Regarding Case 2, clear evidence exists of the ability of trees and woodlots to regenerate degraded land, and protect agricultural production from climate hazards while improving water usage efficiency. Major knowledge gaps relate to the trade-offs between production and resilience, and the levels of agro-ecosystem complexity needed for resilience. The watershed services of forests are important for social adaptation as shown in Case 3, but it is difficult to measure and evaluate their effectiveness, in particular because of the complex processes and different spatial scales involved. A limited number of studies provide evidence linking forested landscapes to reduced climate vulnerability. Although a number of controversies still need to be resolved, the importance of forest hydrological services for human well-being should not be disregarded.

Controversies also exist in Case 4 with regards to the protective role of mangroves during extreme storms. Nevertheless, mangrove forests can be very effective in buffering coastal settlements from the impacts of lower-grade cyclones, typhoons, coastal flooding, erosion, and sea-level rise. Uncertainties remain about the characteristics of ecosystems in determining their protective role from different types of hazards. In Case 5, clear evidence exists of the ability of trees and woodlots to regulate microclimate in urban areas. Major issues relate to opportunity costs and feasibility: the assumption that EBA offers an easy approach to adaptation can be misleading, as experience in Durban has shown.

Our literature search was not geographically restricted; however, most retrieved papers were about developing countries, with the exception of Case 5 (urban areas). One reason may be linked to our focus on vulnerability and adaptation to climate threats, as developing countries are generally considered the most vulnerable,[116,117] despite their experience of dealing with climate-related risks.[118] Another reason may be linked to our choice of analyzing only forests and trees. For example, we found some studies about coastal ecosystem management and vulnerability reduction in Canada, the USA, and the UK,[119–121] but dealing with salt marsh or mudflats rather than forests. The presence of mangrove forests in the tropics has thus put emphasis on tropical countries. A third reason is that the wealth and technology of the richest countries may have allowed them to substitute engineered services for ecosystem services.[122] For example, the degradation of water regulating services has been compensated by improved water sources, water treatment plants or irrigation, and flood control infrastructures. Similarly, the loss of ecosystem services benefiting agriculture has been compensated by increased use of chemical fertilizers and pesticides.[122,123] In this context, adaptation to climate change in developed countries is less often linked to ecosystem services than in developing countries.

The review shows that the effectiveness of ecosystem services in reducing vulnerability to climate is influenced by characteristics, such as topography, geology, soils, ecosystem diversity and structure, and climate. Consequently, an EBA strategy that is effective in one region might not be in another. Careful selection of tree species is also needed in any EBA project, with considerations based on site characteristics and the type of ecosystem service prioritized under the specific climatic conditions. The extent and location of the restored or conserved ecosystems and their structure and composition have an influence on their effectiveness in minimizing risks—e.g., the location of forests in a watershed (Case 3) or the structure of mangroves (Case 4).

The reviewed articles also highlight that the feasibility of EBA strategies depends on a variety of socioeconomic and governance factors that need to be taken into account during the planning of adaptation actions. Community involvement and ownership are key aspects that need to be considered for the success of any EBA programme.[21,23,37] Adaptation initiatives should not only concentrate on the ecological performance of the measures, but also on the economic benefits that can be obtained with the appropriate enabling conditions.[17,21,23,30] Education, capacity building, and extension services will also be needed, among other interventions, to move from short-term coping strategies that focus on resource extraction to ecosystem management and adaptation, particularly for Cases 1 (products)[15,17,21,24,30] and 2 (agriculture).[22,23,28] Securing well-defined property and access rights are other conditions that can make the difference between short-term extractive strategies for coping and sustainable ecosystem management for adaptation.[23,24,34,37] Given that adaptation to climate change requires both short- and long-term actions, institutions and policies to enhance sustainable forest management are needed, both for their provisioning and regulating functions. This review recognizes that socioeconomic and governance factors critically influence forest ecosystem management toward EBA effectiveness. A thorough discussion on the socioeconomic and governance factors of EBA could be the subject of another review paper.

Many studies assess or mention the multiple benefits of ecosystems for human adaptation or well-being. For example, studies on the protective role of mangroves also consider the economic benefits for livelihoods based on fisheries and honey, timber, and charcoal production among others.[33,34] In holistic coastal management, ecosystems are not considered as just ‘bio-shields’, but are valued for the bundle of ecosystem services that they provide. More generally, Case 1 (products) is often relevant in association with other cases in rural contexts, for example 2 (agriculture), 3 (watersheds), or 4 (coasts). Case 5 (cities) can also be associated with Cases 3 (watershed) and 4 (coasts), as cities depend on upstream forests, or some on coastal ecosystems.

Nevertheless, it is important to consider that trade-offs between ecosystem services can also occur. For example, a reforestation project targeting the reduction of landslide or coastal disaster risk through mono-specific or exotic species plantations may provide few products for local communities. Conversely, certain climate-resistant tree species that can be used for diversification with quick returns (e.g., *Eucalyptus*), might affect water availability for people. Exotic plantations of *Casuarina*, a species often used in coastal areas at the detriment of local species, raise concerns about biodiversity and other ecosystem services.[96] Furthermore, different stakeholders can perceive different benefits from the same ecosystem services, which can be complementary, but also competitive.[124] Trade-offs often occur between different spatial scales as well, e.g., if forest conservation for watershed protection reduces the vulnerability of downstream populations, but increases the vulnerability of upstream communities who have restricted access to land and forests.

Other aspects that need to be considered in adaptation decisions include cost-efficiency, co-benefits, and feasibility. Forests and trees can often provide benefits with regards to several of these cases, as well as co-benefits in terms of biodiversity, climate change mitigation, or other ecosystem services such as recreation in cities. EBA measures can be more flexible than adaptation approaches based on infrastructure. Decisions on EBA must consider these multiple aspects, in spite of the uncertainties.

EBA should not be pursued alone, but rather as part of an adaptation portfolio. For example, the use of forest products is important for livelihood diversification, but not as a stand-alone strategy. In the case of coastal defences, as mangroves do not fully protect against any extreme event, climate change adaptation or disaster risk reduction plans should also include alert systems or disaster preparedness for example. There can be limits to EBA in other cases as well. Landslide risk reduction with reforestation on very steep slopes is almost impossible to achieve and other measures, or even relocation of settlements, might have to be considered. EBA can also complement engineering solutions, such as coastal dykes (the grey infrastructure) supported by mangroves (the green infrastructure).

CONCLUSION

We reviewed the scientific literature related to EBA with forests and trees and distinguished five cases where forests and trees can support the adaptation of local communities and the broader society to climate variability and change: (1) Forests and trees providing goods to local communities facing climatic threats, (2) Trees in agricultural fields regulating water, soil, and microclimate for more resilient production, (3) Forested watersheds regulating water and protecting soils for reduced climate impacts, (4) Forests protecting coastal areas from climate-related threats, and (5) Urban forests and trees regulating temperature and water for resilient cities. The literature provides evidence that EBA with forests and trees can reduce social vulnerability to climate hazards, but uncertainties and knowledge gaps remain, particularly for regulating services in watersheds and coastal areas.

The review shows that there are a limited number of studies related specifically to ecosystem services and human vulnerability to climate variability and change. However, an abundant literature on ecosystem services can be used to fill knowledge gaps on EBA. For example, it was shown in Case 3 (watersheds) that hydrological studies provide useful information about the role of forest services in watersheds, even though they do not address climate variability or change. The same can be said about studies on forest products and livelihoods (Case 1), trees and agriculture (Case 2), or mangroves and tsunamis (Case 4). Furthermore, although most reviewed papers dealt with current climate variability rather than climate change, their findings are useful to the perspective of adaptation to climate change.

We need to better understand the efficiency, costs and benefits, and trade-offs of EBA with forests and trees. We do not only need science for EBA (e.g., filling knowledge gaps related to ecosystem functions), but also testing and evaluating different interventions. Pilot projects under implementation could serve as learning sites and existing information could be systematized and revisited with a climate change adaptation lens. Adaptive management and learning-by-doing are essential components of EBA strategies where efficient monitoring and evaluation systems are key.

Combining monitoring systems at different levels (local, landscape, regional) will provide a rich set of information on feedbacks and dynamics in socioecological systems. Involving stakeholders, and especially the beneficiaries of ecosystem services, in the monitoring process will enhance overall adaptive capacity, incentives to learn, and the delivery of early warnings related to environmental change. The main challenge lies in creating the enabling conditions and processes for innovation, flexibility, and iterative and incremental learning.

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