The linkages between biodiversity and climate change adaptation

A review of the recent scientific literature

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Contents

1 Executive Summary

The impacts of climate change are already being felt, and will continue to increase in magnitude. Countries are now starting to develop and implement adaptation policies to cope with these impacts. Adaptation strategies tend to focus on technological, structural, social, and economic developments, and the linkages between biodiversity and adaptation are often overlooked. Nevertheless, biodiversity is linked to climate change adaptation in three main ways; biodiversity can play a role in societal adaptation, biodiversity can be impacted by societal adaptation strategies, and biodiversity conservation is a sector that requires adaptation strategies in its own right.

Scientific literature on the **role of biodiversity in climate change adaptation** is scarce, but there is a growing body of evidence suggesting that ecosystem-based adaptation can be a cost-effective adaptation strategy across the major adaptation sectors. Adaptation strategies that aim to enhance the resilience of ecosystems to enable the continued provision of goods and services can be particularly important for poor people, who are often directly dependent upon their natural resources and have little access to technical measures.

Coastal adaptation: Coastal defences have traditionally relied upon 'hard defence' structures such as sea walls. However, evidence suggests that resilient coastal ecosystems, including mangroves, coral reefs, sand dunes and salt marsh can play an effective role in coastal protection. In addition, coastal ecosystems provide resources such as fish, and allow more flexibility to adapt to uncertain changes. They can also act as a buffer against extreme events. However, coastal ecosystems will not reduce impacts in all cases. Integration of 'hard defence' measures with proper land use planning and ecosystem management is increasingly being promoted.

Adaptation in the water sector: Natural freshwater systems provide vital water regulation services, and can play a role in adaptation to water scarcity, as well as flooding. Actions to reduce degradation of watersheds, through reduced deforestation, afforestation, and soil conservation can lower vulnerability to drought; and the maintenance and restoration of the water regulating services of wetlands is important for flood control. As with coastal defence, the need for integration of improved watershed management with technological measures is receiving increasing attention, though not yet at the policy level.

Adaptation in agriculture: Diverse agricultural systems, incorporating new varieties of crops and crop diversification, are likely to be essential in maintaining food production under changing temperature and water conditions. Such agricultural systems are clearly dependent upon a range of crops, for which the maintenance of agrobiodiversity is critical. 'Good practice' natural resource management, including water and soil conservation is also likely to play a major role in agricultural adaptation, particularly in drylands. Agroforestry, intercropping food crops with tree stands, has been identified as a promising option to improve resilience of agricultural systems to climate change.

Forest adaptation: Discussion of forests in relation to climate change tends to focus on their role in mitigation. However, forests provide a range of regulating services whilst providing important resources to those who depend on forests for their livelihoods, and can be particularly important during extreme events. Maintaining intact natural forests and selecting appropriate mixes of species for afforestation is likely to enhance their resilience to climate change, supporting their contribution to both mitigation and societal adaptation.

Adaptation in the urban environment: The incorporation of more green spaces, including the planting of trees, can play a role in urban adaptation by reducing heat stress and improving drainage during times of flood. Despite this, biodiversity is often overlooked in urban design and adaptation plans.

Health: Although the importance of biodiversity for health is recognised, few links have yet been made to the role of biodiversity in adaptation to the health impacts of climate change. This is an area for further research.

The contribution that biodiversity can make to societal adaptation will differ according to the circumstances, and in many cases technological solutions will be required. Analysis of the costs and benefits of adaptation options is uneven, and further research is required in this area. However, available evidence suggests that integrated management strategies, incorporating ecosystem management into broader cross-sectoral adaptation policies as a complement to structural and technological measures, are likely to result in more sustainable adaptation. This will require significant institutional support, which currently appears to be lacking.

The **impact of adaptation strategies on biodiversity** has been shown to be negative in many circumstances, particularly in the case of 'hard defences' constructed to prevent coastal and inland flooding. This can result in maladaptation in the long term if it removes natural flood regulation properties of coastal and freshwater ecosystems, for example. Conversely, adaptation strategies that incorporate natural resource management, such as improved agricultural practice, can be beneficial for biodiversity. The information available in this area is limited, as few adaptation strategies have been implemented.

There is an urgent need for **adaptation in the biodiversity conservation sector**, as the impacts of climate change on natural ecosystems are already being observed and are likely to increase in magnitude. This is required not just to achieve the conservation of biodiversity for its own sake, but to maintain the role of biodiversity in contributing to societal adaptation. The conservation sector is only recently beginning to develop adaptation measures, but strategies such as improved protected area design, maintaining habitat connectivity in the wider landscape, and reducing other anthropogenic pressures are likely to increase the resilience of biodiversity to climate change. Increasing the resilience of ecosystems to climate change also supports their role in climate change mitigation.

Ultimately, a broad perspective is required, focusing on how ecosystems can be managed and conserved in order to deliver ecosystem services in a changing climate, within the context of overall adaptation policy. There needs to be greater consideration of synergies and trade-offs in adaptation policy and planning, including improved understanding of the underpinning role of biodiversity, to avoid maladaptation and develop cost-effective responses to the impacts of climate change.

2 Introduction

2.1 Adaptation

The impacts of climate change are already being felt, and will continue to increase in magnitude. They include rising sea levels, increased drought and flooding, and impacts on agriculture. Until recently, efforts have been focused on the development of appropriate mitigation measures to reduce the scale of these impacts. However, the need to develop adaptation strategies to cope with the impacts to which we are already committed, or to which we are likely to be committed in the future, is becoming increasingly recognised (Goklany 2007; Pielke *et al.* 2007; Stern 2007).

According to the IPCC Fourth Assessment Report (AR4), adaptation can be defined as the '*adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities'* (IPCC 2007). Adaptation strategies aim to reduce the vulnerability or enhance resilience in response to these 'actual or expected changes' and associated extreme events, and will be required in both human and ecological systems (Adger *et al.* 2007). Currently, adaptive capacity is uneven both across sectors and within societies (Adger *et al.* 2007). The most vulnerable to the impacts of climate change are likely to be those in Least Developed Countries (LDCS), and Small Island Developing States (SIDS).

Adaptation is receiving increasing attention under the United Nations Framework Convention on Climate Change (UNFCCC). The Nairobi Work Programme on impacts, vulnerability and adaptation to climate change was established under the Subsidiary Body for Scientific and Technological Advice (SBSTA) in 2005. The five-year programme has the aim of assisting all Parties to the convention, especially developing countries, LDCs, and SIDS on matters regarding improvement of understanding and assessment of impacts, vulnerabilities and adaptation; and to make informed decision on practical adaptation actions and measures (UNFCCC 2008). Adaptation was also identified as one of the five key building blocks for a strengthened future response to climate change in the Bali Action Plan. Many LDCs have developed National Adaptation Plans of Action (NAPAs), which identify priority adaptation projects required to cope with the immediate impacts of climate change.

Although there are now a number of funds for adaptation, they are widely considered to be inadequate. Estimates of the sums needed to fund adaptation range from $10-86 billion per year. These estimates are orders of magnitude higher than the sums generated under the existing funds (Ayers & Huq 2008; Harmeling & Bals 2008).

2.2 Biodiversity and adaptation

There is some recognition of the importance of ecosystems to adaptation in the text of the UNFCCC. Article 2 states that the ultimate objective of the convention is to stabilize greenhouse gases '*at a level that would prevent dangerous anthropogenic interference in the climate system'*. It then asserts that '*Such a level should be achieved within a time-frame sufficient to allow ecosystems to adapt naturally to climate change*'.

Moreover, Article 4 includes as a commitment of all Parties that they shall: '*Cooperate in preparing for adaptation to the impacts of climate change; develop and elaborate appropriate and integrated plans for coastal zone management, water resources and agriculture, and for the protection and rehabilitation of areas, particularly in Africa, affected by drought and desertification, as well as floods'* Consideration of the underlying ecosystems is crucial to successful adaptation in all these sectors. More specifically, biodiversity is intimately connected to climate change adaptation in at least three ways:

1. Components of biodiversity can play a significant role in strategies for societal adaptation to climate change, and are particularly important for reducing the vulnerability of the poor and disadvantaged. This review will consider the role of biodiversity in the coastal, water resource, agricultural, forest, urban, and health adaptation sectors, including adaptation to extreme events.

2. Many of the strategies adopted for societal adaptation, especially those dependent on engineering and technology, can have significant negative impacts on biodiversity, and these will differ between sectors.

3. The components of biodiversity are themselves subject to considerable impacts from climate change, as established by Kapos *et al.* (2008) in the background documents for the first meeting of the Second AHTEG on Biodiversity and Climate Change. There is, therefore, a need for adaptation strategies within the conservation sector, both to conserve biodiversity for its own sake, and to maintain the role of biodiversity in societal adaptation.

This report reviews the literature published since the IPCC 4AR on the linkages between biodiversity and climate adaptation, focusing on these three topics in turn. This structure reflects the divisions in the literature on biodiversity and adaptation, and provides a useful way of organizing this literature review. Nevertheless, there is a risk that it can obscure some of the underlying connections between the three topics. This point will be taken up in the conclusion. Keyword searches in ISI Web of Knowledge and Google Scholar were carried out to obtain a broad coverage of the available literature. As the peer-reviewed literature in this area is limited, grey literature was also used

3 The role of biodiversity in societal adaptation to climate change

Strategies for societal adaptation to climate change are generally based on engineering structures, technological developments, and economic diversification. However, the evidence that adaptation strategies based on natural resources can play an important and cost effective role as part of integrated adaptation strategies is growing (ProAct Network 2008; Abramovitz et al 2006). This evidence is grounded in the known links between ecosystems and human livelihoods (Abramovitz et al 2006).

Ecosystems provide a number of services that play a significant role in maintaining human well-being. These include provisioning services, such as food, fuel and fibre, regulating services, such as carbon storage and water regulation, supporting services, and cultural services (MA 2005a). A recent study has estimated that welfare losses due to the loss of ecosystem services could be equivalent to 7% of annual consumption by 2050 (European Commission 2008). Although the detailed linkages between biodiversity and ecosystem services are not always well understood, it is widely recognised that maintaining biodiversity promotes the continued provision of services under environmental change (Carpenter, Bennett & Peterson 2006; World Bank 2008; Palumbi *et al.* 2009; Worm *et al.* 2006).

The poor are often the most directly dependent on ecosystem services. It has been estimated that three quarters of the world's poorest people (those living on less than $2 per day) depend on the environment for a significant part of their livelihoods (WRI 2008). In Africa, for example, more than 70% of the population earn their living in agriculture, and most of the remaining population depend on exploitation of other natural resources through hunting, fishing, and use of forest products (Enow & Muhongo 2007).

It is for this reason that adaptation strategies that enhance the resilience of ecosystems, ensuring the continued provision of goods and services, can be particularly important for poor people (Adger, Arnell & Tompkins 2005a; AIACC 2007; Ravindranath 2007; Reid & Huq 2005; Thomas & Twyman 2005). Poor people with low adaptive capacity are vulnerable to the impacts of climate change, which will contribute to the loss of their natural resource base (Eriksen *et al.* 2007). Ecosystems, particularly those that have already been degraded are likely to be severely impacted by climate change (Fischlin *et al.* 2007). A recent study has projected that annual losses to the Namibian economy due to the impacts of climate change on natural resources alone could be up to 5% of GDP, and that this will affect the poorest members of society (Reid *et al.* 2008). It has been suggested that environmental degradation is lowering the resilience of people to climate change in the Niger Delta (Uyigue & Agho 2007), and in developing countries globally (Huq & Ayers 2007). Thus, the need to build resilience in ecosystems to maintain their productivity is often stressed in the development literature as a necessary part of adaptation strategies, particularly for vulnerable communities (Corfee-Morlot *et al.* 2003; Nkem *et al.* 2007; Reid *et al.* 2008; Tompkins & Adger 2004b; Tompkins & Adger 2004a; WRI 2008).

Similarly, in Small Island Developing States (SIDS), many people depend upon biodiversity resources that are already under stress (CICERO & UNEP/GRID-Arendal 2008). Adaptation strategies that involve the sustainable management and use of resources are likely to enable SIDS to become more resilient to climate change (Cherian 2007).

In addition, natural resource management strategies are more accessible to local communities than strategies based on infrastructure and engineering (Hedger & Cacouris 2008; Reid & Huq 2005), and community-based adaptation projects often involve the management of natural resources (Huq *et al.* 2005). Rehabilitating natural resources such as farm and grazing lands, forest, watersheds, and fisheries have become a central focus on a project-level scale across Asia and Africa (AIACC 2007). Biodiversity is also included in many National Adaptation Plans of Action (NAPAs), which identify priority adaptation requirements in Least Developed Countries (LDCs), as these requirements are often linked to natural resource management (Shaw 2006). An analysis of the 30 NAPAs available in 2008 showed that 25 Parties identified adaptation projects related to biodiversity, 8 of which were small island developing states (SIDS) (Webbe 2008).

Although reflected on a project basis and in some NAPAs, the role of biodiversity in adaptation has received little attention at the scale of national and international adaptation policy (Kalame *et al.* 2009; Nkem *et al.* 2007). A small number of countries do identify natural resource management related actions in their adaptation plans (Webbe 2008), but it generally tends to be overlooked; particularly in developing countries.. The remainder of Section 2 outlines the contribution that biodiversity can make to societal adaptation across the various adaptation sectors.

3.1 Coastal adaptation

3.1.1 Coastal defence

Adaptation in the coastal sector has received the most attention in the literature to date. This is largely due to the fact that coastal societies and ecosystems are particularly vulnerable to climate change, and impacts are already being felt. Even a one meter rise in sea level, the lowest expected this century, could displace nearly six million people across South Asia and 37 million people along the river deltas of East Asia (Dasgupta *et al.* 2007).

Protection strategies for sea level rise range from ‘hard’ defences, such as sea walls, dykes, and tidal barriers to ‘soft’ defences such as natural resource management (Adger *et al.* 2007). In most developed countries, ‘hard’ defences are preferred, particularly in built-up areas (Kirshen, Knee & Ruth 2008). These defences have often been built with little regard for the integrated nature of the coastal ecosystem, and can require costly repairs and upgrades (Duxbury & Dickinson 2007). The cost of infrastructure to prevent against storm surges and floods in the UK alone has been estimated at $18 – 56 million annually (Mani 2007). More recent strategies include ‘managed realignment’ or ‘coastal retreat’, whereby infrastructure is moved inland to reduce the risk of impacts and allow the development of inter-tidal ecosystems, or 'accommodation' where planning restrictions prevent the development of infrastructure on floodplains or at certain distances from the shore (Glick, Staudt & Stein 2009; ProAct Network 2008). Managed realignment of hard protection structures due to increased erosion rates, and high costs of maintenance is being trialled in the UK (ProAct Network 2008). Options for adaptation in the coastal zone are shown below in Table 1.

Table 1. Major adaptation strategies for the coastal zone (UNFCCC 2006)

Protection	Retreat	Accommodation
Hard structures: dykes, sea walls, tidal barriers	Establishing set-back zones	Early warning systems, hazard insurance
Soft structures: dunes or wetland restoration, beach nourishment	Relocating threatened buildings and hard protection structures	Land use planning (building and agricultural practice)
Indigenous Options: afforestation	Phasing out development in exposed areas	Improved drainage and desalination

Biodiversity can play a role in a number of coastal defence strategies. Soft engineering solutions incorporate activities such as planting of marsh vegetation in the intertidal zone and wetland restoration (Morris 2007). Coastal wetlands can absorb wave energy and reduce erosion through increased drag on water motion, a reduction in the direct wind effect, and directly absorbing wave energy (Day, Jr. *et al.* 2007). The accretion of sediments also maintain shallow depths that decrease wave strength (Koch *et al.* 2009).

Biodiversity based adaptation measures are receiving increasing attention in developing countries, particularly SIDS, where adaptive capacity is low and local communities depend upon their natural resource base (Cherian 2007). Mangroves, for example, can provide physical protection to coastal communities whilst providing provisioning goods and services such as productive fisheries; offering both physical protection and economic gain to the most vulnerable people (Adger *et al.* 2005a; McKinnon & Webber 2005; Reid & Huq 2005). It has been estimated, that the value of mangroves for coastal defence in Malaysia is US$ 300,000 per km based on the cost of hard engineering that would otherwise be required (ProAct Network 2008). Nearly 12,000 hectares of mangroves planted in Vietnam at a cost of US$1.1 million, saved an estimated $7.3 million per year in dyke maintenance whilst providing protection against a typhoon that devastated neighbouring areas (Reid & Huq 2005).

Recent research has suggested that natural systems can actually be more effective at protecting coasts from erosion and flooding than hard defence structures (Costanza *et al.* 2008; Hanak & Moreno 2008), although this will not be the case in all situations, and modelling of societal responses to sea level rise in different areas rarely produces the same optimal response (Tol *et al.* 2006). Risk-based analyses have shown that generally it is advantageous to use expensive structural protection in highly developed areas, and 'softer' approaches such as land management in less developed areas (Hulme 2005; Kirshen *et al.* 2008). In addition to being more cost-effective, strategies focused on resource management tend to provide co-benefits such as biodiversity conservation, and allow for more flexibility to adapt to uncertain changes in the future

(Costanza *et al.* 2008; Kirshen *et al.* 2008; Koch *et al.* 2009; Luisetti, Turner & Bateman 2008).

Although coastal vegetation has significant potential in climate change adaptation, it requires a holistic management approach, with full participation from local authorities and communities (Tanaka 2009). Currently, ecosystem management initiatives for coastal protection tend to lack a scientific basis (Mascarenhas & Jayakumar 2008). Different species of mangrove, marsh plants, and seagrass have different wave attenuation capacities (Koch *et al.* 2009). In order to provide optimal coastal protection, mangrove belts need to be maintained at a certain width and thickness and planted vegetation needs to be given time to mature (ProAct Network 2008). The conditions in which coastal vegetation will offer protection are also not entirely known. There will be areas in which dunes play a better protective role, and others in which mangroves are more suitable (Danielsen *et al.* 2005). For example, conversion of coastal sand dunes to protective plantations might result in maladaptation as sand dunes can provide better protection (Bhalla 2007).

Integrated management of coastal ecosystems is required because of the interconnectivity of coastal systems. For example, mangrove protection against hurricane damage extends to increasing resilience of coral reefs (Gilman *et al.* 2008; Mumby & Hastings 2008; ProAct Network 2008; Grimsditch 2006). Waves approaching a coastal area travel across reefs and through seagrass beds before reaching mangroves, and the wave attenuation is not provided by one ecosystem alone (Koch *et al.* 2009). When planting vegetation for coastal defence, it is important to include species with tolerance for flooding and broad ranges within the intertidal zone (Morris 2007).

It is also important to reduce coastal ecosystem degradation. Many services provided by coastal and marine ecosystems are in decline (Leslie & Mcleod 2007). Although climate change could result in a 10-15% loss of mangrove, the current rate of deforestation far exceeds this threat (Alongi 2008). This can reduce the resilience of coastal vegetation to climate change, and remove their capacity to act as a physical barrier (Gilman *et al.* 2008; ProAct Network 2008; Tornqvist & Meffert 2008), increasing vulnerability of coastal communities to extreme events (Danielsen *et al.* 2005). Sand extraction of dunes for construction increases vulnerability to storm surges (Sudmeier-Rieux 2006), and anthropogenic threats to reefs reduces their protective and fish provisioning services (Adger *et al.* 2005b; Kunkel, Hallberg & OPPENHEIMER 2006; Meadows & Brosnan 2008). For example, water flow may actually be accelerated through channels of fragmented reefs (Cochard *et al.* 2008). Environmental degradation can also reduce the potential for economic recovery due to loss of traditional livelihoods (Adger *et al.* 2005b). However, most communities have little experience of managing for resilience (Gibbs 2009), and the concept itself is not fully understood (Gilman *et al.* 2008). Capacity building in this area is likely to be required.

3.1.1.1 Integrated Coastal Zone Management

It is becoming increasingly recognised that integrated management of the entire coastal zone is required. Integrated Coastal Zone Management (ICZM) is being promoted due to the recognition that a combination of sustainable protective measures is required for the coastal zone (Duxbury & Dickinson 2007). Where hard structures are built without consideration for the impacts on buffering coastal ecosystems, they can actually reduce the adaptation potential of the coast, a process known as 'maladaptation' (Glick *et al.* 2009). Mangroves, for example, respond to sea level rise and coastal erosion by retreating inland (Alongi 2008), but may be significantly impacted where there is reduced area to move landward (Alongi 2008; Gilman *et al.* 2008; Jagtap & Nagle 2007). Land use planning is therefore necessary to avoid this 'coastal squeeze' (Gilman *et al.* 2008). In Louisiana, the drainage of wetlands and starvation of natural sediments from the construction of canals and levees contributed to the land subsidence that lowered some areas below sea level (Glick *et al.* 2009).

Economic studies have suggested that considering integrated adaptation strategies can be beneficial, both for ecosystems and society (Costanza *et al.* 2008; Sugiyama, Nicholls & Vafeidis 2008). The management of coastal ecosystems can be combined with hard defence strategies and land use planning (Jenkin 2005). For example, salt marshes can protect landward sea defences whilst providing a habitat for rate plants and migratory birds (Hulme 2005; Luisetti *et al.* 2008). This has also been recognized in developed countries. In the Netherlands, flood prevention policy is shifting from dykes to realignment and ecosystem restoration, due to the difficulties of continuous dyke maintenance (Pasche *et al.* 2008; ProAct Network 2008). However, although similar ICZM activities are also being explored in the UK (de la Vega-Leinert & Nicholls 2008), coastal governance and the need to involve a variety of stakeholders means that progress is slow (Milligan *et al.* 2009; Mcfadden 2008). There are also tradeoffs to be made. Managed retreat often only occurs on low value land and can be costly and difficult to implement, whereas accommodation through creation of new floodplain habitats is subject to the choice that this land can be lost to the sea (Hulme 2005; Richards *et al.* 2008).

Much of the literature surrounding the role of ecosystems in coastal protection is focused on reducing extreme event impacts, which will be discussed in section 3.1.3

3.1.2 Fisheries

In addition to coastal protection, mangroves, coral reefs, and other coastal ecosystems play an important role in fisheries (FAO 2007; Glick *et al.* 2009). Recent studies in the Gulf of Mexico have estimated that mangrove fish and crab species account for 32% of small-scale fisheries landings, and that coastal ecosystems contribute an estimated 77% of the global ecosystem-services value calculated (Martinez *et al.* 2007). The resources provided by coral reefs are particularly important for SIDS (Walling & Creary-Chevannes 2004). In a study in the Philippines, 90% of all fishers, recognized the role of mangroves as a nursery site, in addition to their role in storm protection (Walton *et al.* 2006).

The vulnerability of fisheries to climate change and the implications for adaptation has not yet been considered on a large scale, but recent evidence suggests that impacts could be significant (Coulthard 2008; Allison *et al.* 2009; Brander 2007). The communities likely to be impacted most heavily include a number of less developed countries, where the most vulnerable groups rely on fisheries for 27% of their protein

(Allison *et al.* 2009). In Bangladesh, a community wetland management programme which protected wetlands from degradation has improved fish catches by an estimated 140% and improved resilience of both the wetland and the community to environmental change. The success of this project led the government to include it in the fisheries strategy to reduce the siltation caused by forest clearance, wetland drainage and flood embankments (WRI 2008).

3.1.3 Reducing extreme event impacts

There is a growing wealth of literature linking disaster risk reduction (DRR) strategies with climate change adaptation. Although there is much uncertainty attached to the role of climate change in increased severity and incidence of extreme events, an increase in disasters such as flooding and hurricanes is predicted (Francisco 2008). These disasters are likely to impact vulnerable areas such as Small Island Developing States (SIDS) and Least Developed Countries (LDCs), particularly in Asia. It has been suggested that management of natural resources can contribute to disaster risk reduction by reducing vulnerability to the event, and increasing adaptive capacity after the event (Sudmeier-Rieux 2006; Francisco 2008). The role of coastal ecosystems has received particular attention in this respect.

A number of studies carried out following coastal disasters such as tsunamis and hurricanes have documented an important role for wetlands, mangroves and coral reefs in coastal protection against extreme events and tropical storms (Danielsen *et al.* 2005; Granek & Ruttenberg 2007; IUCN 2008; Olwig *et al.* 2007; Perez-Maqueo, Intralawan & Martinez 2007; Francisco 2008; Mattsson *et al.* 2009; UNEP-WCMC 2006). Although tsunamis are not related to climate change, they provide an evidence base for the protective role against storm surges in general. Coastal ecosystems can provide a buffer against the wave impacts and also decrease the strength of the waves. Forest canopies in wetlands can diminish wind flow and reduce surface waves, whilst shallow water vegetation can limit wave build-up (Day, Jr. *et al.* 2007).

A Rapid Environmental Assessment by IUCN following the tsunami of 2004 found a clear correlation between damage of inland areas and human modifications to the coastline, with mature sand dunes especially effective in protection (Bambaradeniya *et al.* 2005). During Hurricane Katrina, levees fronted by extensive wetlands escaped substantial damage, suggesting that a well managed combination of hard and soft protection can play a role in climate change adaptation (Day, Jr. *et al.* 2007), and that the re-establishment of protective habitats could be important even for built up areas (Glick *et al.* 2009). Hydrological models and simulations have suggested that a 100m wide mangrove forest belt can reduce wave flow by 90% (Alongi 2008), and that coral reefs offer protection against tsunamis (Kunkel *et al.* 2006) to add weight to observational reports. It has been estimated that coastal wetlands in the U.S. alone provide $23.2 billion per year in hurricane protection (Costanza *et al.* 2008), and that the coastal protection value of mangroves exceeds their direct use value by over 97% (Sanford 2009).

Despite the wide range of anecdotal reports and modelling exercises, there remains little empirical evidence that coastal ecosystems can protect against extreme events (Feagin 2008; Granek & Ruttenberg 2007), leading some to question the validity of diverting adaptation funds to coastal ecosystem management (Cochard *et al.* 2008). Reports that areas with mangrove and tree shelterbelts were significantly less damaged than other areas have been questioned due to the large number of caveats inherent in the studies (hdouh-Guebas & Koedam 2006), whereas other studies have found no such role for coastal ecosystems (Kerr, Baird & Campbell 2006).

Indeed, although a number of studies support the role of coastal ecosystems in coastal storm protection, they note that it has limitations (Kerr & Baird 2007). The presence of sand dunes, mangroves, and coral reefs made little impact in the epicentre of the 2004 tsunami, although they reduced the power of the smaller waves in Sri Lanka (Adger *et al.* 2005b). Few studies take into account the variability between energy and speed of waves (Cochard *et al.* 2008). Ecosystem services are not linear across space and time. Wave attenuation may be higher in summer where biomass is highest for example, or when the tide is low and it cannot be assumed that vegetation will automatically provide coastal protection (Koch *et al.* 2009). Protection by vegetation such as mangroves depends upon the stand size, density, species composition, and structure, and degraded ecosystems are less likely to function as buffers (Cochard *et al.* 2008; Koch *et al.* 2009; Tanaka 2009; Alongi 2008). A recent study using satellite imagery and field measurements found that survival rate of mangroves during extreme events increased with increasing stem diameter, but that the mangrove belt was mostly destroyed following inundation at depths greater than 6m (Yanagisawa *et al.* 2009).

It is important to recognise that ecosystems alone cannot reduce the impacts of storms, and that a balance of social capital and built defences are also needed (Perez-Maqueo *et al.* 2007). The limitations of ecosystems in coastal protection should be recognised for coastal planning, as should the ways in which protection by ecosystems can be enhanced (Tanaka 2009). This can be linked to the resilience of the ecosystem to environmental change (Sudmeier-Rieux 2006), which has been discussed in section 3.1.1.

3.2 Adaptation in the water sector

The impact on water resources is likely to be the major challenge posed by climate change. In some regions, too little water will lead to droughts and desertification, whereas in others too much water will lead to increased flooding (FAO 2007).

Desertification is considered to be one of the most threatening processes to livelihoods of the poor (MA 2005b) with more than 300 million Africans living in drought or drought-prone areas; a number likely to be increased in Africa and on a global scale due to climate change (IPCC 2007). A new report projects that by 2030, 47% of the world population will be living in areas of high water stress, especially in Africa, with 24 to 700 million people expected to be displaced because of water scarcity (UNESCO 2009). Africa and Asia are expected to be the most impacted, with adaptation costs in the sub-Saharan urban water sector estimated at between 10 and 20 per cent of current overseas development assistance to the region (Muller 2007). Adaptation options for water shortage range from water use controls to the building of reservoirs and diversion of rivers into drought prone areas (Obersteiner 2006). Options for adaptation to flooding include structural defences similar to those used in coastal protection, watershed management, and flood planning. The major adaptation strategies for water related impacts are outlined in Table 2.

Table 2. Major adaptation strategies in the water sector (Obersteiner 2006)

Water stress	Flooding
Desalination	Structural protection
Ground-water pumping	Watershed management
Water transfer	Land use planning
Removal of invasive vegetation	Flood forecasting
Improved water efficiency (including demand-side management)	Relocation of populations
Soil moisture conservation	Insurance

Biodiversity can play a role in adaptation strategies to both drought and floods through watershed, wetland, forest, and agricultural management (Kundzewicz *et al.* 2008; Berry *et al.* 2008). Maintenance or restoration of forest and wetlands, for example, can reduce run-off in times of flood and also increase water retention during droughts (Krysanova *et al.* 2008).

3.2.1 Adaptation to water stress

Reduced vulnerability to drought, particularly in dryland regions, requires improved soil and water management (Falkenmark & Rockstrom 2008; Stringer 2008). The regulation of water flows in dryland regions have been strongly linked to the proportion of land covered by forest, grassland, and wetland, and maintaining vegetation cover can assist in adaptation to drought (Falkenmark & Rockstrom 2008). Upland watersheds play a vital role in water regulation. Run-off from mountainous areas in SIDS is often the major supply of water (Mata & Budhooram 2007), and in the Phillipines, watersheds are a critical part of the national economy (Lasco *et al.* 2008). Often these watersheds are degraded, and their rehabilitation is one adaptation option (MacKinnon 2007). Planting trees on slope fields, mini-terracing for soil and moisture conservation, and improved pasture management can also complement actions such as building of small-scale infrastructure in water resources management (World Bank 2008). Natural resource management has been included in the NAPA of the Niger, where water stress is the major issue, and the reduction of pressure on freshwater resources is receiving attention in Brazil where the use of pesticides has impacted water quality in many areas (Hedger & Cacouris 2008). Soil erosion measures such as conservation tillage can be coupled with rain water harvesting and are activities that can be undertaken by communities (Paavola 2008). Water management is cross-sectoral, and is particularly relevant to agricultural adaptation. It will be discussed in more detail in section 3.3.

3.2.2 Adaptation to flooding

In addition to water provisioning services, watersheds can reduce flooding and sedimentation whilst improving water quality downstream. A study of upland forests in a watershed in Madagascar has estimated their flood protection value at $126,700, and peat bog in Sri Lanka that buffers floodwaters from rivers have an estimated annual value of more than $5 million (Emerton & Bos 2004; Sudmeier-Rieux 2006). In the Morogoro region of Tanzania, reduced river flow and increased flooding has been attributed to deforestation in the mountains, and it has been suggested that effective governance of soil, forests and water resources are needed as adaptation measures, along with improved social capacity (Paavola 2008). Ecuador and Argentina have integrated forests and wetlands into their 'living with floods' strategies (World Bank 2008), and reforestation is recognised as an important option for adaptation in the watersheds of the Phillipines (Lasco *et al.* 2008). Viet Nam includes measures such as integrated management of watersheds in its disaster reduction planning, along with forest management, and soil and water conservation (Sudmeier-Rieux 2006). Large-scale afforestation projects in China have been carried out with the aim of reducing flooding and increasing water conservation, and countries of Central America are collaborating to protect watersheds and forest (Abramovitz et al 2006).

Ecosystem management is also an effective adaptation strategy at the river basin scale and can be an alternative to the development of dams, which have a high environmental impact. (Mata & Budhooram 2007). In developed countries, cost effective flood reduction strategies that allow re-growth of vegetation alongside rivers and establish vegetation buffers along streams, combined with the reduced development of infrastructure, are being promoted in some areas (Nelson *et al.* 2008). Some evidence that this can be an effective strategy has been provided in a modelling scenario exercise, which suggested that a combination of wetland restoration and hard defences provides optimal flood protection (Berry *et al.* 2008). Riparian floodplains can also help to reduce the levels of water pollution following extreme events (CCSP 2008). In Europe, the conservation or restoration of river floodplains has been included in a number of flood reduction strategies (Zaunberger, Agne & Miko 2009), although there are many new river management plans that do not include such measures (Krysanova *et al.* 2008).

3.2.3 Integrated Watershed Management

Water resource adaptation options need to be able to function under uncertain future climate change, but many adaptation measures do not sufficiently account for this (Krysanova *et al.* 2008). The building of dams and large-scale irrigation systems for example cannot completely protect against floods and can also damage the adaptation capacity of other sectors, an example of maladaptation (Palmer *et al.* 2008; Fraiture *et al.* 2007). Technical measures such as desalination, pumping of deep groundwater, and water treatment are very resource intensive (Krysanova *et al.* 2008). Increasingly it is becoming recognised that water management requires an integrated approach, through 'integrated watershed management' which includes natural resource management along with social measures and infrastructure development (Galaz 2007; IUCN 2008; Kundzewicz *et al.* 2008; Bates *et al.* 2008). In principle, restoring and protecting freshwater habitats and watersheds and managing natural floodplains is a key element of such an approach (Glick *et al.* 2009). Reduction of pressure on freshwater resources would be beneficial regardless of the scale of the future impact (Kundzewicz *et al.* 2008), whereas activities such as river regulation, wetland drainage, intensive agriculture, and deforestation degrade freshwater habitats and lower adaptive capacity (Krysanova *et al.* 2008). The Government of India has initiated an Integrated Watershed Management Programme to restore degraded regions through rehabilitating and maintaining the natural resource base, which involves soil moisture conservation measures such as contours, afforestation, vegetating drainage lines, and engineering structures to collect rainwater (Bhandari, Suruchi & Ulka 2007).

These strategies recognize wetlands and river basins as an integral part of the hydrological regime (Harrison *et al.* 2008). It has been widely suggested that an ecosystem approach including wetland and floodplain management and restoration should not be viewed as an alternative to technological approaches such as reservoirs and irrigation systems, but as a complement to them (Mata & Budhooram 2007). However, there appears to be a lag between our understanding of interconnected freshwater resources and adaptation strategies implemented by policy makers (Galaz 2007).

Watershed management should be planned according to local conditions. For example, planting of some tree species could have negative impacts on water flow in some areas (Bhandari *et al.* 2007). In South Africa, 'Working for Water' programmes have been initiated to remove invasive tree species from water catchments where water-thirsty species have reduced the annual river flow by approximately 7% in South Africa (Mukheibir 2008). Similar impacts have been seen in China, where the monoculture tree species chosen for plantations were not suitable for the area (McVicar *et al.* 2007).

3.3 Adaptation in agriculture

The production of food crops is perhaps the most climate-dependent economic activity. Climate change is already affecting agriculture in developing countries negatively, and this situation is likely to worsen (IPCC 2007), with significant impacts on crop yields and the productivity of grazing lands and livestock expected, through changes in temperature, precipitation, water availability, salinity, and the abundance of pollinators , pests and diseases (Rosenzweig & Tubiello 2007). Impacts will not be uniform, but will vary across regions and require a number of different adaptation strategies (Berry *et al.* 2008). Agricultural production is the main economic activity for rural communities of vulnerable regions such as Africa and India (Chatterjee, Chatterjee & Das 2005; Osbahr *et al.* 2008). In some countries in Africa, yields from rain-fed agriculture could be reduced by up to 50 per cent by 2020 (IPCC 2007). In Central and South Asia, crop yields could fall by as much as 30 per cent by 2050 as a result of climate change; India alone could lose 18 per cent of its rain-fed cereal production (Lobell *et al.* 2008). For agriculture in the world's drylands, the challenges are especially large due to predicted changes in hydrological cycles characterised by both increased droughts and increased risks of flooding (Falkenmark & Rockstrom 2008). Depending on the region and the available resources, options for adaptation range from relatively inexpensive changes, such as shifting planting dates or switching to an existing crop variety, to much more costly measures including the development of new crop varieties, increasing chemical and other inputs and irrigation systems (Rosenzweig & Tubiello 2007). Broadly speaking, the options for adaptation in agriculture include: (i) changes in the locations of cultivation (i.e. opening new areas for cultivation); (ii) changes to the crops cultivated, including substitution by new crops, new varieties and crop diversification; and (iii) changes to agricultural practice, including irrigation and soil management regimes and the use of agricultural inputs. Biodiversity plays an especially strong role in supporting the latter two.

3.3.1 Changes in location of cultivation

Climate change will lower the suitability of some areas for agriculture, and open up new suitable zones, particularly in northern latitudes Areas of cultivation could shift geographically, following shifting climatic zonations (Rosenzweig & Tubiello 2007), and livestock may be moved to new zones (Berry *et al.* 2008).

3.3.2 Changes to crops cultivated

Within a given region, different crops are subject to different degrees of impact from current and anticipated climate changes (Lobell *et al.* 2008). One major avenue for adaptation is the substitution of different crops more suited to changing and new conditions. Rice, maize, and wheat contribute roughly half of the calories currently consumed by the world's poor (Lobell *et al.* 2008), the remainder of the world's food supply comes from a wide variety of other crops including sorghum, millet, sweet potato, cassava, groundnuts, sugar cane and many different beans. Adaptation in agriculture will include the adoption of many of these crops in areas and farms where they were not previously grown. For example, in a vulnerable community in India, growing new crops together with higher value crops for commercial sale was among the adaptation measures already being adopted to help cope with drought (Chatterjee *et al.* 2005). The most common adaptation strategies used by farmers in South Africa and Ethiopia include the use of different crop varieties, (Bryan *et al.* 2009). Adopting new crops and varieties has also been an important aspect of recovery from extreme events in Zimbabwe (Chigwada 2005). Where salinisation is a problem due to rising sea levels or excessive water extraction, the introduction of salt tolerant crops and varieties can help to ensure continued agricultural production (Galvani 2007).

Further, the use of currently under-utilised crops can help to maintain diverse and more stable agro-ecosystems, (Bowe 2007). The use of indigenous and locally adapted plants, can enhance the capacity of communities to cope with changing climatic conditions by providing alternative food and income sources, that may be better suited to changing conditions (FAO 2007; Eriksen 2005). For example, the bambara groundnut, an ancient grain legume grown, cooked, processed and traded mainly by subsistence women farmers in sub-Saharan Africa has great potential to provide continued production in the face of growing climate variability (Azam-Ali 2007).

Developing climate-tolerant crop and livestock varieties and genotypes, such as those tolerant to drought, heat stress, disease, and saline conditions is another avenue for increasing the adaptive capacity of farmers (Aggarwal 2008; Kesavan & Swaminathan 2006; Ortiz *et al.* 2008). Such selection will often depend on locally used varieties and crop wild relatives as sources of characteristics that contribute to drought or flood tolerance or the ability to withstand highly variable climate (Bailey-Serres & Voesenek 2008). However, changes in cultivars and livestock races can bring other climate-related risks. For example, adapting winter cereal production by using longer-maturing cultivars is dependent on there being enough precipitation over the extended growing season to sustain grain filling (Rosenzweig & Tubiello 2007). Increasingly, new crop varieties are being developed through genetic modification that can incorporate individual traits and does not depend on a long breeding programme. There is a danger that these costly (and in some cases environmentally risky approaches) may target environmental tolerances that are not appropriate to eventual real climatic changes in large areas of the world.

In addition to substituting new crops, races and cultivars with those currently in use, adaptation may involve crop diversification. Although empirical evidence is lacking, it is likely that farming practices can be more easily adapted to cope with changes in water availability or temperature if a larger number of crop varieties are available (Hedger & Cacouris 2008; Weltzien *et al.* 2006; Kouressy *et al.* 2008; Reidsma & Ewert 2008; Bowe 2007; Smale 2005; Reid, Simms & Johnson 2007; Thomas *et al.* 2007). Crop diversification and mixed cropping is currently being used in Brazil and Ghana, to increase the chances that at least one crop will survive and produce a harvest (Leavy & Lussier 2008). At its most successful, diversification also provides increased income by ensuring that there are several different income streams available. (Leavy & Lussier 2008). Research on agro-ecosystems in China has suggested that diversification of agriculture is a promising poverty reduction strategy but requires efficient use of resources (Hengsdijk *et al.* 2007).

The adoption of new crops and development of new varieties and cultivars, whether through breeding or genetic modification, are clearly dependent on the availability of a range of crops; the maintenance of agrobiodiversity is therefore critical to such adaptation (Kotschi 2007; Fowler 2008). Ensuring the continued survival of crop wild relatives that provide additional genetic diversity for breeding and the development of new varieties is also crucial (Jarvis, Lane & Hijmans 2008).

3.3.3 Changes in agricultural practice

Changing many different aspects of farming practice, ranging from planting and harvest dates to water and soil management practices, will also be an important part of most agricultural adaptation strategies.

In many cases alterations to planting and or harvest dates are helpful in dealing with climatic changes (Rosenzweig & Tubiello 2007; Bryan *et al.* 2009). Early sowing has been found to be helpful in some cases (e.g. (Luo *et al.* 2009), but it can be problematic in drier environments. Double cropping may even be possible in regions where the length of the growing season is increased (Meza, Silva & Vigil 2008), but it is likely to increase the use of pesticides and fertilizers. The success of changes to cropping dates is also dependent on the availability of pollinators and therefore on changes to biodiversity within the surrounding landscape.

Globally, agriculture consumes more than 3000 litres of water per person per day to meet food demand (Molden 2007). 60% of all agricultural production comes from rainfed land, while 40% comes from irrigated areas (Fraiture *et al.* 2007). Changing precipitation regimes will likely alter this balance. Managing water supplies and demands will be vital to adaptation of agriculture worldwide, and especially in drylands (Falkenmark & Rockstrom 2008). Development of new irrigation systems is costly, improved capture storage and use of rainwater is less so (Shiferaw, Okello & Reddy 2007). Water conservation is particularly important in India as 68% of the agriculture is rainfed, making watershed development through soil and water conservation vital for adaptation to climate change (Bhandari *et al.* 2007; Chatterjee *et al.* 2005). The use of water-efficient and or perennial crops can reduce demand for water (Bell et al., 2008) (Reid *et al.* 2007), and inexpensive measures to enhance water productivity of agricultural systems through soil and watershed conservation can improve rural incomes and diversify livelihood streams whilst increasing carbon sequestration (Molden 2007; Noble 2007; Castillo *et al.* 2007; Hartmann, Hediger & Peter 2007). In Senegal, where farmers have had to adapt to successive droughts and a drying climate, planting dense perennial hedges as windbreaks helps to improve the microclimate for crop growth (Seck, bou Mamouda & Wade 2005).

In other areas, drainage or dyke building may be necessary to reduce flooding probabilities and the impacts of extreme events, and to make lowland areas usable for agriculture (Olesen 2006), but such measures can be costly and have negative impacts on biodiversity. Less expensive measures include raising beds and floating gardens, both of which are being adopted in flood-prone areas such as Bangladesh (Leavy & Lussier 2008).

Soil conservation and enhancement are also an important part of adaptation in agriculture. This can include structural methods such as terracing and stone bunding (Shiferaw *et al.* 2007), the use of chemical or organic fertilizers, changes to tillage practices, and agroforestry techniques. On the whole, good practice agriculture such as crop rotation, contour tiling, minimum tillage, the use of vegetation buffer strips, and agroforestry can all play major roles in adaptation (Berry *et al.* 2008). Conservation agriculture, which involves minimizing soil disturbance and maintaining cover through plantings or mulches, and organic agriculture (Muller 2009; Huang 2008) are promising options for adaptation in farming communities because they increase soil carbon and water retention, decreasing vulnerability to extreme weather events (WRI 2008; Lal *et al.* 2007; FAO 2007; Thomas *et al.* 2007). They also reduce the need for nutrient inputs and use of heavy machinery. In drylands, agricultural practices such as the use of shadow crops can enhance resilience by providing protection against extreme rainfall, and increasing infiltration into the soil (Blanco 2004). Vegetation litter, the use of nutrient enriching plants, reduced use of fertiliser, crop diversity, and maintenance of forest can also be utilised as adaptation strategies (Blanco 2004). Sand and dust storms can be reduced through the use of forest shelterbelts and improved cohesion of soil particles through practices such as mulching (Sivakumar 2005). Replanting of indigenous trees can reduce soil and wind erosion, as can ridging and mulching (Abramovitz et al 2006). Farms using agroecological practices such as soil conservation have been found to be more resilient to hurricanes (Reid & Swiderska 2008).

Agroforestry, intercropping food crops with tree stands can improve biophysical resilience and promote income diversification (Verchot, V *et al.* 2005) and is one of the most promising options for helping communities adapt and become resilient to the impacts of climate change. It provides permanent cover leading to soil conservation and microclimatic buffering, opportunities for diversification of the agricultural systems, and improved efficiency of water resources (Rao *et al.* 2007), and is especially important to smallholder farmers with significant biodiversity benefits (Verchot, V *et al.* 2007). Agroforestry and many other forms of agricultural good practice including reduced tillage, were originally designed as ‘‘best practice’’ management strategies, aimed at enhancing the long-term stability and resilience of cropping systems in the face of climate variability or of increased cultivation intensity (Rosenzweig & Tubiello 2007). They also serve an important role in climate change mitigation by enhancing carbon stocks within the agricultural landscape (Kandji *et al.* 2006). Further they both increase and depend on biodiversity and ecosystem services.

The viability of the many different options available for adaptation in agriculture is dependent on the availability of financial human and natural resources and on the willingness of farmers to consider the options (Reidsma 2007; Brondizio & Moran 2008). To date, there have been few examples of policy level decisions to promote adaptation in the agriculture sector (Ziervogel *et al.* 2008), and one of the challenges for adaptation researchers is to understand how best to address the information needs of policy-makers and report and communicate agronomic research results in a manner that will assist the development of food systems adapted to climate change (Gregory *et al.* 2008; Bryan *et al.* 2009). It has been suggested that adaptation strategies should invest in sustainable agriculture, promoting soil and water conservation and preserving biodiversity (Leavy & Lussier 2008), and should be part of a strategic governmental response (Bryan *et al.* 2009).

3.4 Forest adaptation

Much of the discussion related to forests and climate change has focused on mitigation, rather than adaptation (Guariguata *et al.* 2008). Although there is a wealth of literature on the ecosystem services provided by forest and the links to livelihoods, little is explicitly related to climate change adaptation. Much of the literature that does exist is related to management of temperate forest (Locatelli *et al.* 2008). However, the role of forests in societal adaptation is becoming increasingly recognised (Eliasch 2008), and has led to the development of initiatives such as the Congo Basin Forest and Climate Change Adaptation (COFCCA) project. Solidifying the links between forests and adaptation will be important to reduce damaging management practices that could lead to maladaptation in the longer term (Nkem *et al.* 2007).

Forests can contribute to adaptation in three main ways; through structural defence against wind and soil erosion, through water regulation, and through the provision of timber and non-timber forest products (NTFPs) (Ogden & Innes 2007; Innes & Hickey 2006; UN 2008; WRI 2008; McEvoy, Lindley & Handley 2006; Paavola 2008; Eriksen *et al.* 2006), as has been discussed in previous sections. On a local scale, forests can provide shade and reduce exposure to heat; for example a study in Kenya found that improved microclimate and catchment properties of a hilltop area were closely linked to good biodiversity status of the forest (Eriksen *et al.* 2006).

Conversely, deforestation is a driving force for loss of ecosystem services and land degradation (Cangir & Boyraz 2008). Forest dwellers and those that rely on forest resources are often the poorest members of society and have low adaptive capacity (FAO 2007; Ravindranath 2007). Where access to NTFPs become marginalized, vulnerability of the poorest people increases (Eriksen, Brown & Kelly 2005; Paavola 2008). Both natural and plantation forests can provide 'safety nets' during periods of food shortage, and can provide an important contribution to food security (Kalame *et al.* 2009; Nkem *et al.* 2007). Community involvement in afforestation projects, for example, can diversify incomes and improve social capacity, reducing the vulnerability to climate change impacts (Guariguata *et al.* 2008; Spittlehouse 2005).

Forests can be particularly important during extreme events. In addition to the provision of 'safety nets', it has been suggested that forest cover can reduce landslide erosion by a factor of 4-5 compared with sites that lack substantial tree root strength, and reduce flooding (ProAct Network 2008; ISDR 2004). In a study of North Pakistan, it was estimated that 56% of all landslides were due to land degradation from deforestation and grazing, and that protective forests would be a cost effective action to reduce disaster risk (Sudmeier-Rieux *et al.* 2007).

In the Amazon, forest has a major role in the regional hydrological regime (Correia, Alvala & Manzi 2008). Forest loss could push some subregions into a permanently drier climate regime, increasing vulnerability of societies to drought conditions (Malhi *et al.* 2008; Betts 2007). Recent research has suggested that there is the potential for large scale die-back of the Amazon rain forest through a combination of degradation and drought (Nepstad *et al.* 2008; Phillips *et al.* 2008), although it is thought that in-tact forests will be more resilient to climate change impacts (Bush *et al.* 2008; Malhi *et al.* 2008; Gullison *et al.* 2007).

Forest management and conservation practices may help to decrease the vulnerability of those who depend on forest services for their livelihoods, while at the same time maintaining the mitigation capacity of forests (Guariguata *et al.* 2008; IUCN 2008). Adaptation in the forest sector (for both natural and plantation forest) can either enhance resistance and resilience of existing forests to climate change, or facilitate adaptation to new conditions (Locatelli *et al.* 2008). Other adaptation options include diversification of the forest economy and the forecasting of potential pest impacts (Ogden & Innes 2007; La Porta *et al.* 2008).

Climate change is rarely factored into forest planning (Nitschke & Innes 2008), possibly due to the uncertainties surrounding the vulnerability of forests to climate change (Chapin *et al.* 2007; Millar, Stephenson & Stephens 2007). A mixture of adaptation measures will be required, depending upon whether the goal is to manage for a specific ecosystem service, or for resilience in general (Locatelli *et al.* 2008). Although a number of adaptation measures have been proposed (Locatelli *et al.* 2008; Guariguata *et al.* 2008; Millar *et al.* 2007; Noss 2001; Ogden & Innes 2007), most of the management practices suggested to date have been generic and based on temperate case studies (Kalame *et al.* 2009).

3.4.1 Natural forest

Evidence suggests that intact forests, particularly old growth forests, will be more resilient to climate change (Betts, Malhi & Roberts 2008; Malhi *et al.* 2008). Strategies aimed at reducing emissions from deforestation and degradation (REDD) could therefore play a significant role in adaptation through maintenance of biodiversity and ecosystems services such as water cycling (Betts 2007; Betts, Sanderson & Woodward 2008; Malhi *et al.* 2008; Nepstad *et al.* 2008). Indeed, it has been suggested that REDD could be the most effective strategy for both adaptation and mitigation, as it is likely to reduce anthropogenic threats to forest (Berry *et al.* 2008). However, badly designed REDD strategies could increase vulnerability of local communities if they are denied access to important forest resources (Locatelli *et al.* 2008)

Many of the management activities required to enhance resilience in natural forest are similar to those required to maintain carbon stocks, such as reduced impact logging, forest conservation and sustainable forest management (Guariguata *et al.* 2008). However, there will also be trade-offs between adaptation and mitigation. For example, maintenance of the genetic diversity of forests is likely to play a large role in forest adaptation to climate change (WRI 2008; Guariguata *et al.* 2008; Kalame *et al.* 2009; Sevrin 2008), but is unlikely to be considered in mitigation strategies. Other strategies for forest adaptation can include the maintenance of different forest types across environmental gradients, expansion of the protected area network, the protection of climatic refuges, the reduction of fragmentation, and the maintenance of natural fire regimes (Glick *et al.* 2009; Locatelli *et al.* 2008; Noss 2001). These conservation strategies will be discussed in more detail in section 5.

3.4.2 Plantation forest

There is significant potential to adapt plantation forests to future conditions. Genetic diversity is likely to be important, and can be obtained through selecting a mix of species and range of age structures, including those that are likely to be adaptable to future climate changes (Guariguata *et al.* 2008; Berry *et al.* 2008). This will be beneficial for biodiversity in addition to improving adaptive capacity. As forest species are long-lived, adaptation measures undertaken now need to be planned according to likely future conditions and be flexible to change (Millar *et al.* 2007; Ravindranath 2007).

Although afforestation can stabilise soils in suitable areas and provide nutrient and water flow benefits, this needs to be considered in the context of current land use and can involve tradeoffs, particularly with water usage (Berry *et al.* 2008; Ravindranath 2007). Selecting appropriate species will include a consideration of the nutrient and water requirements of an area. An example can be given of the largest monoculture plantation in the American tropics in Venezuela, which suffered a large scale tree mortality as a result of water stress during the 1997 El Nino (Guariguata *et al.* 2008). This is another example of a potential trade-off between adaptation and mitigation. Forest plantations for carbon sequestration have generally been established using genetically uniform stock with high growth rates, but low adaptive capacity, which will ultimately diminish their capacity in mitigation (Innes & Hickey 2006).

Afforestation in unsuitable areas, using unsuitable crops and monocultures can have significant impacts on biodiversity, soil erosion, nutrient cycling, and water regulation (Campbell *et al.* 2008).

The central role that forests can play in local adaptation has not been translated into broader adaptation policy (Kalame *et al.* 2009; UN 2008; Nkem *et al.* 2007). This is true both on national scales and under the UNFCCC (Locatelli *et al.* 2008). Forests are widely seen as carbon sinks for sequestration payments (Kalame *et al.* 2009), and there are significant socio-economic and political barriers to mainstreaming adaptation into sectoral forest policies (Kalame *et al.* 2009). Although forestry is generally not a priority in adaptation policy (Locatelli *et al.* 2008), a number of the NAPAs prepared by LDCs do have forest projects within their adaptation priorities (Guariguata *et al.* 2008). Developing countries that have identified forest adaptation priorities need further guidance to enhance the adaptive capacity of their forests (Guariguata *et al.* 2008).

3.5 Adaptation in the urban environment

The role of biodiversity in the urban environment is less intuitive than for other sectors. However, the urban environment is a large adaptation sector, and should not be overlooked. The majority of the global population live in cities and will suffer impacts of climate change, mainly through overheating (with higher temperatures expected in cities than in rural areas), flash floods, and extreme weather events (Smith & Levermore 2008). ‘Structural’ adaptation measures in the urban environment can include improved building design (for increased ventilation, shading etc), increased use of air conditioning, and improved drainage through more permeable surfaces (McEvoy *et al.* 2006). Adaptation measures related to sea level rise in coastal areas and river basins have been discussed in section 3.1.

Biodiversity can play a role in urban planning through expanse of green areas for cooling, improved use of natural areas for drainage and flood reduction, and urban tree planting for structural integrity and removal of pollutants (McEvoy *et al.* 2006; Berry *et al.* 2008). ‘Urban greening’ can improve the microclimate by modifying heat absorption (Smith & Levermore 2008), whereas paving over areas covered by vegetation and water reduces heat loss and increases vulnerability to flooding (Grimm *et al.* 2008). Increasing ‘blue space’ (e.g. lakes and canals) is also recommended for cooling and reduced risk of flooding (Grimm *et al.* 2008).

Clearly, structural measures are required for adaptation in the urban environment. However, a recent analysis of the built environment in Boston has suggested that a combination of both structural and ‘green’ adaptation measures is the optimal strategy to reduce the negative effects of climate change in the built environment, and that considering integration with land use management and coordination amongst institutions is a necessary response to climate change (Berry *et al.* 2008; Kirshen, Ruth & Anderson 2008). Despite this, ‘green space’ is often overlooked in urban design and adaptation plans (McEvoy *et al.* 2006). A recognition of the ecosystem services and economic benefits that can be provided through incorporating ecology into urban design will be important for future sustainable city design (Grimm *et al.* 2008).

3.6 Health

Climate change is likely to have major impacts on health through heat exposure, extreme weather events, air pollution, malnutrition, reduced water quality and availability, water borne diseases, and spread of disease vectors (Kjellstrom & Weaver 2009; WHO 2008).

Although there is a growing body of literature supporting the importance of biodiversity for health (Chivian & Bernstein 2008), few links have yet been made to the role of biodiversity in adaptation to health impacts. Productive ecosystems are necessary for food production, freshwater production, fuel, waste management, and waste management (Corvalan, Hales & McMichael 2005) and the role of biodiversity in adaptation to extreme event impacts, heat exposure, water stress and food production have already been discussed. It has been reported that approximately one quarter of the global disease burden is due to modifiable environmental factors and that 42% of incidences of malaria are associated with policies and practices related to land use, deforestation, water resource management (Pruss-Ustun & Corvalan 2006). This would appear to be an area that requires increasing attention in the future.

3.7 Integration across sectors

This report has focused on separate adaptation sectors, as this is how the literature is generally organised. However, the need for integrated adaptation strategies across sectors to avoid maladaptation is becoming increasingly recognised (AIACC 2007). For example, there is a high level of interdependence between agriculture and water resources, where good watershed management can act synergistically to improve agricultural practice, whereas bad management can have a negative impact and vice versa (Lasco *et al.* 2008). Natural resource management in particular tends to run across a number of sectors.

The literature suggests that although integration of adaptation across sectors is preferable, including the integration of environmental measures, this will require significant institutional capacity (Agrawal 2008; Zaunberger *et al.* 2009). Integrating natural resource management into adaptation in particular requires considerable institutional support, and this is currently lacking (AIACC 2006; Eriksen *et al.* 2006; Kalame *et al.* 2009; Locatelli *et al.* 2008; Tompkins & Adger 2004a). Linkages are rarely made between adaptation policy and issues of governance and land tenure, which are key in developing adaptive capacity to manage resources (Agrawal 2008). One case study in the Philippines suggested that although there were significant synergies between adaptation options in the forest, agriculture, and water sectors, there were trade-offs involved at the institutional level due to tight budget constraints (Lasco *et al.* 2008).

Although such discussions are beyond the scope of this review, institutional networks to support the inclusion of biodiversity and the effective participation of local communities in adaptation strategies are likely to be a key determinant of the integration of biodiversity into adaptation (Adger *et al.* 2005a; Barbier 2006; Bryan *et al.* 2009; FAO 2007; Resurreccion, Sajor & Fajber 2008; Matthews & Quesne 2008).

4 Adaptation strategies and their impact on biodiversity

There is very little literature surrounding the impacts of adaptation strategies on biodiversity, as few adaptation measures have actually been implemented (Paterson *et al.* 2008; Adger *et al.* 2007). However, potential impacts can be identified through our knowledge of likely adaptation measures and the environmental impacts of past management practices. The Netherlands, England and France have begun developing policy for climate change adaptation, in which the requirement to perform Environmental Impact Assessments (EIAs) and Strategic Environmental Assessments (SEAs) on adaptation projects have been recommended, as well as the need to consider ecosystem-based planning (Wilson & Piper 2008). This is based on the recognition that considering biodiversity in the design and operation of infrastructure projects can reduce environmental costs and increase the sustainability of the project (Quintero 2007). The environmental impacts of non-biodiversity based adaptation measures will be discussed in this section. When considering the impacts of adaptation strategies on biodiversity it is important to consider tradeoffs, such as the implications for local incomes and adaptive capacity.

4.1 Coastal defence

4.1.1 Protection

Most of the literature available on this topic is related to the ‘hard’ structures constructed for defence against coastal erosion and sea level rise. Coastal protection, particularly in developed countries, has traditionally been in the form of dykes, seawalls, and tidal barriers, and construction in this area is likely to continue (IPCC 2007). It was recognised in the IPCC 4AR that structures such as seawalls and dams can alter sediment deposition, prevent inland migration of vegetation in response to changing sea levels, and impact upon salt marshes (IPCC 2007). This impact of hard defence structures is well documented, and there is evidence that this ‘coastal squeeze’ and altered sediment deposition is threatening mangrove ecosystems (Gilman *et al.* 2008; Gilman, Ellison & Coleman 2007; Jagtap & Nagle 2007), in addition to tidal flats, saltmarshes, and dunes (Glick *et al.* 2009).

Few studies have considered the impact of hard defences on coastal ecology. Recent research has shown that beaches protected by hard defences suffer reduced availability of habitat and macroinvertebrates due to the loss of upper intertidal zones, which has led to reduced species richness and abundance of shorebirds and seabirds (Dugan *et al.* 2008). One area that requires increasing attention is the impact of coastal structures on fish ecology. A recent study has suggested that species assemblages differ between natural and artificial reef structures, and that it is unclear whether artificial structures will be effective fish habitat (Clynick, Chapman & Underwood 2008). This will be particularly important in areas where defence structures impact upon mangrove and coral reef ecosystems that provide nursery grounds for fish. Sea wall construction has also been noted to have impacts on plant diversity at the upper borders of salt marshes (Bozek & Burdick 2005).

Habitat can also be created by engineered structures such as dykes and seawalls (Berry *et al.* 2008). A number of studies in Sydney Harbour, Australia, have found that intertidal molluscs (key species in rocky shore ecology) do occur on seawalls but with differing levels of abundance and diversity that has uncertain implications for intertidal biodiversity (Moreira 2006; Blockley 2007; Chapman 2006). There is also some evidence that habitats protected by hard coastal defence structures support invasive species, such as non-indigenous macroalgae (Vaselli, Bulleri & Benedetti-Cecchi 2008; Bulleri, Abbiati & Airoldi 2006).

It is not just 'hard' protection measures that can impact upon biodiversity. Beach nourishment is a widely used 'soft protection' approach to deal with coastal erosion. Although there is much uncertainty, it is through that beach nourishment can have significant biodiversity impacts through the dredging of habitats for sand material, which can bury shallow reefs, reduce fish habitats, reduce invertebrate densities, and impact upon turtle nesting (Bilodeau & Bourgeois 2004; Colosio, Abbiati & Airoldi 2007; Fanini *et al.* 2009; Glick *et al.* 2009; Peterson & Bishop 2005; Speybroeck *et al.* 2006; Speybroeck *et al.* 2007). However, it has been suggested that with proper planning beach nourishment would have a lower impact than the use of hard defences (Jones, Gladstone & Hacking 2007), and that a better understanding of the ecological impacts is required (Jones *et al.* 2008).

There can clearly be significant environmental impacts from hard defence construction. However, trade-offs need to be considered where hard protection is necessary. It has been estimated that hard protection in Germany reduces $300 billion of damage (Sterr 2008). Similarly, although flood control schemes in Bangladesh such as sluice gates reduce fish production and species richness, they can be beneficial for agriculture (Halls *et al.* 2008).

4.1.2 Managed realignment and accommodation

The strategies of managed realignment and accommodation, which can involve the movement of infrastructure inland and improved land use planning (Ellis 2008), can be beneficial for biodiversity as they are often combined with activities such as wetland restoration (Berry *et al.* 2008). Moving coastal defences inland can create new intertidal habitat (Berry *et al.* 2008; Hardaway *et al.* 2002), and can provide breeding and feeding grounds for water birds (Crowther 2007). It can also facilitate the inland migration of mangroves (Gilman *et al.* 2008), and can reduce coastal squeeze for wetland habitats more generally (Berry *et al.* 2008). Accommodation reduces building on coastal areas and can involve habitat restoration.

However, one study has suggested that whilst the realignment of embankments can reduce the requirement to constantly upgrade flood defences, there are clear incompatibilities between flood defence and habitat restoration objectives that need to be evaluated (French 2008). Movement of structures inland can facilitate the transition of salt marsh, the habitat thought to be most at risk from coastal defences, to mud flats (Gardiner *et al.* 2007). At realignment sites in the UK, biological monitoring has been poor, and although new habitats have been created they lack the biodiversity found in surrounding natural habitats (ATKINSON 2004). In moving infrastructure there is also the potential for adverse impacts on biodiversity at the relocation sites (Berry *et al.* 2008), and careful land use planning is clearly required.

Accommodating floods is likely to be necessary in some areas such as SIDS, and will lead to large-scale migration of environmental refugees, with unquantified environmental impacts.

4.2 Water management

River flood defence systems are similar to those used in coastal defence. River breakwaters, dykes, dams, levees, and floodgates are all large structures used to prevent flooding around rivers, and can have significant environmental impacts. In addition to loss of natural vegetation along river banks, these structures can reduce connectivity between lakes, rivers, and riparian zones, and reduce sediment flows; contributing to the loss of wetlands (Huang *et al.* 2007; ProAct Network 2008). This can actually increase flooding and reduce water quality downstream (Abramovitz et al 2006). They can also act as a barrier to the movement of aquatic species such as fish (Berry *et al.* 2008; Krysanova *et al.* 2008; Reid & Swiderska 2008).

In addition to defence from flooding, a number of engineering adaptation options are being employed to reduce water shortages, ranging from construction of dams and reservoirs to engineering to improve river flow, and diversion of rivers. There is little information available on this topic, but large infrastructure projects can have major environmental impacts, particularly diversion of rivers which requires extensive landscape planning (Larsen, Girvetz & Fremier 2007). Large-scale dams can cause deforestation, loss of habitats, impact on aquatic biodiversity, and reduce the services provided by downstream flood plains and wetlands (Mata & Budhooram 2007). Removing river vegetation to improve river flow can negatively impact biodiversity by disconnecting wetlands from water sources (Berry et al. 2008).

4.3 Agricultural practice

Many of the adaptation practices discussed for agriculture such as development of perennial wheat varieties, mixed cropping, agroforestry, and organic farming are all likely to be beneficial to biodiversity. This is because soil, water, and nutrient conservation are all vital for adaptation. However, as discussed in a review of agricultural mitigation strategies (Campbell *et al.* 2008), 'worst case' management practices will always have the potential to impact biodiversity (Berry *et al.* 2008), a review of which is beyond the scope of this report. Impacts will depend on local circumstances and conditions.

There are a number of specific adaptation strategies for agriculture that are likely to impact upon biodiversity. Draining wetlands to increase agricultural production during flooding, the use of dykes, and increases in irrigated agriculture can all have impacts to biodiversity through loss of habitat, soil erosion and eutrophication (Olesen 2006), as can increased use of pesticide to control increased pest outbreaks. These actions are also likely to have a negative impact on adaptation options in other sectors (Berry *et al.* 2008). The replacement of crop systems with monoculture crops selected for specific traits such as drought resistance could increase soil erosion and pesticide use whilst also lowering resilience to climate change (Abramovitz et al 2006). Similarly, the use of genetically modified crops could have as yet unquantified environmental impacts, with risks of invasiveness and reductions in genetic fitness. However, these crops offer great potential for adaptation and trade-offs may be required (Berry *et al.* 2008).

Intensified agriculture, whilst providing gains in the short-term, can degrade natural resources and lead to maladaptation in the long term, particularly for the most vulnerable groups (Paavola 2008). This highlights the need for integrated policy development across sectors (Berry *et al.* 2006).

4.4 Urban environment adaptation

Many of the strategies proposed in urban adaptation, including the increase of 'green' and 'blue' space, and urban tree planting (as discussed in section 3.5) will be beneficial to biodiversity (Berry *et al.* 2008; McEvoy *et al.* 2006). However, man-made streams and canals will not be substitutes for the loss of natural systems (Grimm *et al.* 2008), and where there is migration from rural areas due to climate change impacts, urbanisation will impact on biodiversity through habitat fragmentation and increased waste production (Grimm *et al.* 2008).

4.5 Health

There is very little information available on the biodiversity impacts of adaptation to the health impacts of climate change. However, the increased spread of mosquitoes could be controlled by draining wetland breeding sites and introducing fish species to control mosquito larvae. This would likely have negative impacts on biodiversity, as would control through the use of chemicals (Berry *et al.* 2008).

5 Adaptation in biodiversity conservation

Intact and resilient ecosystems can play a role in climate change adaptation, in many cases providing cost-effective options to reduce vulnerability to climate change impacts (see above). The range of current and potential impacts of climate change on biodiversity (Kapos *et al.* 2008) means that adaptation strategies are needed in the biodiversity conservation sector to address and minimise these impacts. Such strategies are needed not only to help achieve conservation goals, but also to ensure that biodiversity can continue to contribute to societal adaptation to climate change and to climate change mitigation.

The IPCC 4AR (Fischlin *et al.* 2007) outlined a number of potential adaptation strategies to reduce climate impacts on ecosystems, including the reduction of anthropogenic pressures, development of appropriate protected area networks, landscape management, controlled fire management, habitat restoration, captive breeding and assisted migration. A limited number of subsequent studies have identified possible adaptation strategies and frameworks for adaptation to maintain biological diversity and the capacity of species and ecosystems to accommodate and adapt to climate change (Berry *et al.* 2008; CCSP 2008; Gayton 2008; Glick *et al.* 2009; Heinz 2008; Huntley 2007; Mitchell *et al.* 2007; Ptato 2008). These include the protection of key ecosystem features or areas likely to act as 'refuges from climate change', maintaining representation and replication of species and ecosystems, and the restoration of damaged ecosystems (CCSP 2008). Nearly all of these strategies have been developed in and for developed countries in temperate regions; very little work has as yet addressed specifically strategies for adaptation in biodiversity conservation in developing and tropical countries. Recent research on adaptation to climate change in biodiversity conservation is reviewed here, organised into *autonomous* and *planned* adaptation.

5.1 Autonomous adaptation

The ultimate objective of the UNFCCC (Article 2; UNFCCC 1992) is to "achieve stabilization of greenhouse gas concentrations *[...] at a level that would prevent dangerous anthropogenic interference [...] within a timeframe that allows ecosystems to adapt naturally to climate change*". Current conservation practices, generally aimed at maintaining species diversity, can facilitate the variation that would allow ecosystems to 'adapt naturally' to environmental change (Berry *et al.* 2008). Indeed, there is some evidence that species have the capacity to adapt (e.g. Skelly *et al.* 2007), as can been seen by range shifts and phenological changes as responses to past climate change (Kapos *et al.* 2008). The full extent to which species will be able to adapt to climate change is largely unknown (Visser 2008), but there are likely limits to natural adaptation, particularly taking into account the scale of projected climate change.

Species may be able to adapt autonomously to climate change by *i*) dispersing to suitable habitats, *ii*) changing their phenotype without a change in genotype via phenotypic plasticity, or *iii*) adapting by genetic change over generations (evolutionary response). The former two may occur rapidly, and have been observed as responses to recent climate change (Kapos *et al.* 2008). However, the main concern is whether species will be able to adapt fast enough to keep up with their changing environment with major biodiversity loss (Visser 2008). Some species will be more able to adapt than others, depending on generation times, ability to disperse, and dependency on other species (e.g. pollinators, hosts for parasites, symbionts) (Baker *et al.* 2004; Best 2007). Potential further constraints to evolutionary responses to climate change include time lag between change and response, and erosion of genetic variation (Skelly *et al.* 2007). It is widely accepted that many species and ecosystems will not be able to adapt naturally to climate change under the timescales predicted, and that planned adaptation responses will be required.

5.2 Planned adaptation

Conservation management in the context of climate change faces several challenges, including resolving the tension between urgency of action (climate change is already having measurable impacts on biodiversity (Kapos *et al.* 2008)) and uncertainty about:

(i) the nature and magnitude of climate change itself in any given location
(ii) the likely responses of species and ecosystems
(iii) the degree to which and ways in which responses will affect each other
(iv) the likely effect of management on responses

There is still relatively little concrete scientific evidence on the effectiveness of different management strategies in relation to climate change, so much adaptation work is still based on ecological reasoning, rather than on extensive research and case studies (Heller & Zavaleta 2009). In the face of these uncertainties, there is a need for proactive management strategies that can quickly be adapted to new circumstances and changing conservation priorities (Lawler *et al.* 2009; Heinz 2008). These will require institutional coordination, incorporation of climate change scenarios into planning, and efforts to address multiple threats simultaneously (Heller & Zavaleta 2009).

5.2.1 Ecosystems

Planning conservation action with full consideration of climate change (and its associated uncertainties) could help to reduce the vulnerability of entire ecosystems (Ravindranath 2007). Species responses will ultimately determine the ability of ecosystems to adjust and persist under changed climates (Gayton 2008); changes in ecosystems will in turn promote further changes in species abundances, distributions and interactions, with the possible breakdown of traditional species relationships, such as pollinator/plant and predator/prey interactions (Backlund, Janetos & Schimel 2008). It has been suggested that ecosystems and communities themselves should not be the focus of conservation actions to adapt to climate change because differential responses among component species will mean certain changes in their composition and identities (Huntley 2007). However, the importance of maintaining ecosystem resilience (Kareiva *et al.* 2007) and its relationship to maintaining adequate extent and diversity of habitat to facilitate species adaptation have repeatedly been emphasized

(Harley & Hodgson 2008; Hopkins *et al.* 2007; Huntley 2007; Mitchell *et al.* 2007). Therefore, many conservation interventions address management at the ecosystem scale, and aim at the continued existence of ecosystems and the provision of the services they provide.

Among the key needs that have been identified as driving conservation actions in the context of adaptation to climate change are:

- the need to maintain adequate populations of species and sufficiently large areas of ecosystems to ensure their resilience and ability to continue to maintain biodiversity and provide other ecosystem services
- the need to ensure functional connectivity between populations and habitats so that species are able to shift their distributions in response to climate change
- the need to reduce other stresses on ecosystems and species

Adaptation to climate change in conservation management at the ecosystem scale, which aims to address these needs, therefore falls into three broad categories:

1. Changes in the extent and design of protected area systems
2. Changes in their management
3. Management of the wider landscape, including efforts to ensure functional connectivity

5.2.1.1 Protected Areas Systems

Protected areas have long been used as an important tool to secure sites that are perceived as important in biodiversity conservation (Williams *et al.* 2005; Lee & Jetz 2008) and to reduce the pressures that affect the ecosystems and species within them. To the extent that they are effective at reducing pressures other than those arising from climate change and that they include areas of high quality habitat, protected areas are potentially important tools for limiting the impacts of climate change on biodiversity (Heller & Zavaleta 2009; Hannah 2008). Extending and/or strengthening protected area networks is frequently emphasized as one of the fundamental options for adaptation to climate change in the conservation sector (Killeen & Solorzano 2008; MacKinnon 2008; Ravindranath 2007; Malhi *et al.* 2008), and is emphasised in a number of proposed adaptation frameworks (Heinz 2008; Mitchell *et al.* 2007; CCSP 2008; Mcclanahan *et al.* 2008).

However, current protected areas were established to conserve species and ecosystems in a stable climate; at best they were designed to conserve particular components of biodiversity as they were distributed at the time of the initial assessment and planning (Lemieux & Scott 2005; Huntley 2007), and at worst they were located in areas where conflicting demands for land were minimal (Mackey *et al.* 2008). As species ranges shift in response to climate change, and ecosystem composition changes as a result, existing protected areas may play a limited role in facilitating biodiversity adaptation to climate change (Hannah 2008; Mackey *et al.* 2008; Rahel, Bierwagen & Taniguchi 2008; Von Maltitz *et al.* 2006; Heller & Zavaleta 2009). For example, vegetation-modeling projects that 37-48 percent of Canada's protected areas could experience a change in terrestrial biome type under doubled atmospheric carbon-dioxide conditions (Lemieux & Scott 2005). Similarly, bioclimatic envelope models project a decline in Natura 2000 sites of habitat suitable to support many of the species they currently protect (Vos *et al.* 2008). The first quantitative study of the exposure of the global protected area network to climate change (Lee & Jetz 2008) has suggested that similar patterns are likely to hold true at global scale.

Therefore, considerable effort will need to be devoted to expanding and redesigning protected areas systems to ensure that they include sufficient area to accommodate management practices that both facilitate change and maintain large populations of species of concern (Huntley 2007). Additional criteria and approaches for consideration in re-designing protected areas systems include: (i) that they should contain large enough core areas of ecosystems that will be relatively un-affected by climate change, which can serve as refugia from changing conditions (Heinz 2008; Mitchell *et al.* 2007; CCSP 2008; Mackey *et al.* 2008; Vos *et al.* 2008; Julius & West 2007); (ii) that they maximize representation of species of concern by including their projected distributions under a changed climate, similar to system planning exercises that are in use for current conditions (Araujo *et al.* 2004); (iii) that they should include the greatest possible degree of habitat diversity, including as far as feasible a full range of combinations of environmental conditions (Huntley 2007). It has also been suggested that expanding reserves preferentially towards the poles and higher altitudes might provide greater scope for adaptation to climate change (Li, Krauchi & Gao 2006), but other authors have pointed out that in many regions, the options for doing this are severely limited by the availability of space and resources (Huntley 2007). Further, design of protected areas systems should consider questions of functional connectivity (see below), take advantage of 'buffer zones' to increase the effective size of reserves (Huntley 2007; Mitchell et al 2007), link habitats in new suitable climate zones with existing relatively 'climate-proof' refugia and include diverse reserve management strategies (see below) (CCSP 2008; Vos *et al.* 2008; Williams *et al.* 2005).

One recent study emphasising the importance of connectivity has suggested that expanding protected area networks could delay loss of species representation under climate change until the middle of the century (Hannah 2008). Unfortunately, there is as yet little concrete evidence on how protected areas will perform in the face of climate change (Heinz 2008). The problem is still greater in the case of the marine protected areas (MPAs), where planning in the context of climate change is relatively recent (McLeod *et al.* 2009). One study found that existing no-take marine protected areas had no positive effect on the response of reef ecosystems to large-scale climate-related disturbance (Graham *et al.* 2008). Although there are expectations that MPAs will promote resilience and faster recovery from climate disturbance, site-specific studies suggest this may not be the case; the effectiveness of such management needs to be assessed across regional spatial scales (Graham *et al.* 2008). A further concern is that reserve expansion is a very expensive option (Von Maltitz *et al.* 2006).

The likely effects of climate change on protected areas systems raises the question of whether these networks should be regarded as fixed in space and time, or whether provision should be made for movement of protected areas boundaries (Pressey *et al.* 2007; Hannah 2008). Precedents exist in the form of areas that currently receive seasonal protection or where temporary restrictions on resource extraction (e.g. fisheries) are imposed. Movable protection is particularly relevant for marine systems where frontal zones and currents are likely to shift with climate change and where the areas involved are potentially enormous (Hannah 2008). The existing concept of 'adaptable' protected areas, whereby conservation status could be applied or removed as an area becomes more or less valuable as species habitat, could be relevant to climate change (Berry *et al.* 2008). The management objectives of individual protected areas and of whole systems will also need to be dynamic, changing as their composition changes over time (Huntley 2007; Mitchell *et al.* 2007), and even the concept of what constitutes a native species may need to be re-considered (Huntley 2007) . On the one hand, it may be appropriate to plan protected areas networks and their management in terms of 'potential native species' (Huntley 2007), and on the other, the arrival of some species that are in no traditional sense introduced but are better suited to new conditions than relict species from earlier conditions may lead to interactions and impacts not unlike those associated with invasive alien species (Dunlop & Brown 2008).

5.2.1.2 Protected Area Management

Ensuring the continued survival of ecosystems and species under changing climatic conditions requires not only to adjustments to the extent and location of protected areas, but also changes in the ways in which they are managed. It is important that reserve management be as well informed as possible by an understanding of the likely impacts of climate change (Mitchell *et al.* 2007; Ptato 2008; Hopkins *et al.* 2007; Backlund *et al.* 2008; Killeen & Solorzano 2008; Brooker, Young & Watt 2007). However, at least in some regions, reserve managers are not aware of likely climate change impacts on their reserves (Schliep *et al.* 2008). Management changes will be needed both to minimise the direct impacts of climate change on protected ecosystems and to reduce other threats not directly linked to climate change.

Managing for reduced climate change impacts will include actions to preserve ecosystem processes such as regeneration and succession, for example through leaving large trees in place to maintain seed sources and favourable microclimates for germination and establishment of new seedlings. In some cases it may also include active restoration of degraded habitats, which may also help to increase the effective size of the reserve (Heinz 2008; Julius & West 2007; Millar *et al.* 2007).

Reducing threats not linked to climate change also needs to be a key goal of protected area management (Mitchell *et al.* 2007; Heinz 2008; Huntley 2007; Dunlop & Brown 2008; Fischlin *et al.* 2007) so that resilience of populations can be maximized and ecosystem function can be maintained. Such threats include over-exploitation of resources, eutrophication, wildfire and invasive alien species. Assessing and improving the effectiveness of protected area management (Hockings, Stolton & Dudley 2004) will be critical in dealing with these threats, as will integrating protected area management with management of the wider landscape, which may often play a major role in regulating the influence of such pressures (see below). The incidence and intensity of wildfire and the impacts of invasive alien species are likely to be further exacerbated by climate change (Dunlop & Brown 2008), so the management objectives and practical management regimes of individual protected areas will need to be dynamic, and to change as the area's composition changes over time (Mitchell *et al.* 2007; Huntley 2007). Many authors emphasise the importance of adaptive management in maintaining the effectiveness of reserves under changing climatic conditions (Hopkins *et al.* 2007; Heinz 2008; Mitchell *et al.* 2007; Heller & Zavaleta 2009).

The management of buffer zones around protected areas is seen as an important tool for maintaining the integrity of protected areas and helping to ensure the continued functionality of their ecosystems and the delivery of ecosystem services, such as water yield regulation, that may be important in societal adaptation to climate change (Mitchell *et al.* 2007; Huntley 2007; Heller & Zavaleta 2009). However, it is important to recognise that their principle role is in increasing protected area effectiveness rather than in contributing directly to adaptation to climate change (Huntley 2007).

5.2.1.3 Functional connectivity

Numerous authors emphasise the importance of ensuring functional connectivity among natural areas in facilitating movement of species and their adaptation to climate change (Huntley 2007; Heinz 2008; Glick *et al.* 2009; Heller & Zavaleta 2009). For example, habitat connectivity has been identified as a particularly important adaptation strategy for many forest species (Roy & de Blois 2008), and could enhance the diversity and resilience of forest ecosystems to climate change (Chapin *et al.* 2007; Millar *et al.* 2007). Upstream-downstream connectivity in rivers and water course is also very important (Hopkins *et al.* 2007).

In many cases, improved connectivity is interpreted to mean the use of continuous habitat corridors, to reduce habitat fragmentation (Matisziw & Murray 2009), both in conjunction with protected areas and as part of broader habitat management (Hannah 2008). They are gaining increasing attention as a tool to facilitate the migration of species, as they could allow species to track environmental changes (Roy & de Blois 2008; Glick *et al.* 2009; Rahel *et al.* 2008; Gayton 2008). However, it is difficult to predict the utility of habitat corridors and the movements of individual species with confidence (Heinz 2008); particularly as the nature and utility of corridors varies greatly among species (Donald 2005; Donoghue 2008; Kettunen *et al.* 2009). In Costa Rica, researchers found that different bird species had different preferences for riverine forest corridors or hedgerows as avenues for movement among habitat patches (Gillies & Clair 2008). A recent review of work on hedgerows found that although some species use hedgerows as corridors, the benefits could not be adequately assessed even at the small scale, and the role of corridors at the landscape level for adaptation to climate change is even less understood (Davies & Pullin 2007). Some authors caution against the justification of large-scale corridors on grounds of climate change, since migration along corridors by standard dispersal mechanisms is unlikely to keep pace with projected change for many species (Pearson & Dawson 2005).

In theory, to be functional corridors would need to span environmental gradients and be a part of broader landscape planning to ensure that they are not threatened by planned infrastructure (Killeen & Solorzano 2008). Many authors sound cautionary notes about the feasibility of establishing such continuous habitat corridors in many situations (Huntley 2007; Hopkins *et al.* 2007; Mitchell *et al.* 2007), and point to the concept of stepping stones of natural and semi-natural areas and to management of the wider landscape to increase its 'permeability' to wildlife as being much more relevant (Von Maltitz *et al.* 2006) and see below). There is also more general concern that, increasing connectivity should not be seen as a substitute for the conservation of large core areas of habitat (Hulme 2005).

5.2.1.3.1 Management of the wider landscape

In addition to improving protected areas and their management, and enhancing connectivity among them, improved planning and management of the wider landscape is agreed to be fundamental to adaptation strategies in biodiversity conservation (Heinz 2008; Hopkins *et al.* 2007; Mackey *et al.* 2008; Wilson & Piper 2008; Heller & Zavaleta 2009). One goal of such improvements is to make the matrix around reserves more attractive to wildlife and therefore more permeable to species movements, which is expected to facilitate their dispersal (Hopkins *et al.* 2007; Mitchell *et al.* 2007; Chapman *et al.* 2003; Donald & Evans 2006). Many studies recommend 'softening' land use practice in the matrix around reserves (Heller & Zavaleta 2009), but provide relatively little detail as to what such changes in practice might entail. In general more diversity friendly practices might include lower intensity farming with reducing agrochemical use (Berry *et al.* 2008), planting and restoration of hedgerows, management and restoration of ditches and ponds and maintenance of field margins and summer fallows (Donald & Evans 2006). In the tropics, agroforestry has great potential to increase the permeability of agricultural landscape (Villamore & Lasco 2008). In non-agricultural landscapes, reduced impact logging, restoration and fire management will be important to maintain forest integrity and increase landscape diversity (Guariguata *et al.* 2008). Management of upland streams to enhance resilience of freshwater bodies will also be important (Conlan *et al.* 2007).

As for protected areas management, management of the wider landscape will need to be done in adaptive fashion to enable it to take account of changes in climate and other conditions (Von Maltitz *et al.* 2007; Hopkins *et al.* 2007; Heinz 2008). Agri-environment schemes are one mechanism to promote such management, and they have the advantage that they are already in use and are adjusted regularly to take account of changing conditions and emerging needs.

These approaches provide multiple advantages in the context of climate change. They increase the amount of habitat available to species that can actually use the matrix, they increase the functional connectivity of landscapes for species that might need to disperse across them, and they reduce many threats not directly linked to climate change. Furthermore, in many cases they will increase the ability of the landscape to provide ecosystem services such as water yield, timber provision, pollination and pest control (Harris *et al.* 2006; Hannah 2008), and which could support societal adaptation (see section 3). In many cases they will also enhance carbon storage, providing a strong link between strategies for adaptation to climate change and those for mitigating it.

5.2.2 Species

Adaptation strategies for species are crucial as they represent the building blocks of ecosystems. Species responses will ultimately determine the ability of ecosystems to adjust and persist under changed climates (Gayton 2008). There are multiple adaptation intervention options available applicable to species. Excluding evolutionary adaptations (discussed under autonomous species adaptation above), species have been classified into four functional groups based on their response to climate change (Von Maltitz *et al.* 2007), which each require different adaptation strategies:

1. *persisters* are tolerant to the new climate of their current location (dealt with in autonomous adaptation);
2. *obligatory dispersers* physically move with the changing climate to track suitable climates, either by dispersing autonomously (see above) or requiring assistance by human assisted translocation or dispersal into suitable habitats;
3. *range expanders* expand into new climatic envelopes that are not currently available but to which the species are already well adapted; these species require either no intervention or if they become invasive need to be controlled
4. *no-hopers* cannot do any of the above and will become prematurely extinct, although may persist under unsuitable climates for some time and might be rescued by ex situ conservation.

5.2.2.1 *In-situ* adaptation measures

In situ conservation measures for species have not been well researched in the context of climate change adaptation, although *in situ* methods are a common conservation strategy. The approach is to increase the resilience of existing ecosystems and species in their current locations through site-based management, restoration and reduction of pressures from sources other than climate change. Removing non-climate pressures from species might give species more flexibility to evolve and adapt to climate change. Fischlin et *al.* (2007) and Heinz (2008) note that this may be the only practical large-scale adaptation policy for migratory species and marine systems. Habitat restoration might provide food and habitat for species, e.g. blocking drainage ditches on peatlands should raise water levels and reduce the vulnerability of cranefly populations to increased temperatures and summer desiccation, and therefore benefit a range of bird species (James Pearce Higgins pers.comm.). Food provision at feeding stations (e.g. urban bird feeders) might give species flexibility to adapt to climate-related pressures. Similarly, controlled fire management, reduction of fragmentation and other habitat managements might positively affect some species. However, there are many pressures affecting species and only a select few could be tackled with limited resources. Further complex species interactions need to be carefully considered before modifying habitats, providing food or changing fire regimes, to avoid negative consequences on other species.

5.2.2.2 Human-aided translocation

Translocation, also referred to as assisted dispersal, migration, or colonization, involves facilitating the movement of animals, plants and other organisms from sites that are becoming unsuitable due to global climate change to other sites where conditions are thought to be more favourable for their continued existence. Translocation has been suggested as one option to facilitate the movement of species into climatically suitable areas where the timescale or habitat fragmentation prevents their ability to move naturally (Glick *et al.* 2009) and has been recommended in US and UK adaptation strategies (Julius & West 2007; Mitchell *et al.* 2007).

Assisted migration can take a number of forms. Planting seedlings adapted to future climates is recognised as a key adaptation strategy in the forestry sector (O'Neill *et al.* 2008). It is also argued that commercial plant nurseries are a form of assisted migration as in Europe, 73% of native species investigated had commercial northern range limits that exceeded their natural range limits, which could provide a 'head start' on migration (Veken *et al.* 2008). More extreme forms of assisted migration involve the movement of species into areas that they had not previously inhabited, but that will now be climatically suitable. Species with small populations, fragmented ranges, low fecundity, or suffering declines due to introduced insects or diseases could be candidates for facilitated migration (Aitken *et al.* 2008). Tested translocation techniques are available for many vertebrate species and some invertebrates (for examples, see Heinz 2008).

However, translocations may have undesirable consequences and opinion is divided as to whether species should intentionally be moved out of their current range and into another area (Mueller & Hellmann 2008; Veken *et al.* 2008). The most controversial aspect is the potential impact on the ecosystem into which the species will be moved. One risk with translocation is that the species could turn invasive. The Monterey Pine which was confined to narrow sections of the California coast, was translocated to South America and has spread to Chile, New Zealand, Australia and South Africa (Fox 2007). By comparing past intracontinental and intercontinental invasions in the United States, Mueller and Hellman (2008) show that the risk of translocation to create novel invasive species is small, but translocated species that do become invasive could have severe effects, particularly fish and crustacean intracontinental invasions (Mueller & Hellmann 2008). Another issue is that translocations may fail, potentially resulting in extinctions. The lack of detailed knowledge about the species and limitations of existing models make it difficult to predict optimal future locations. Different models might give different projections, e.g. comparing static vs. dynamic models for carnivores in North America (Carroll 2007), climate vs. climate-habitat models for birds in Spain (Suarez-Seoane, Osborne & Rosema 2004), and even different populations within a species may respond differently (Tolimieri & Levin 2004). Beale *et al*. (2008) suggest that climate might not be determining species distributions at all. The characteristics of both the species and the translocation sites (see section on ecosystems above) need to be carefully considered (Hunter 2007), and many studies fail to adequately research the ecological requirements, community interactions, and genetic diversity of the species (McLachlan, Hellmann & Schwartz 2007).

In all such cases, the advantages and disadvantages of translocation need to be carefully assessed and decisions should consider the best option to minimise species loss under climate change as well as options to facilitate natural population spread, along with an awareness of unintended consequences (McLachlan *et al.* 2007; Hoegh-Guldberg *et al.* 2008). Hoegh-Guldberg *et al*. (2008) have developed a decision framework which can be used to outline potential actions for assisted colonization under a suite of possible future climate scenarios.

5.2.2.3 *Ex-situ* measures: captive breeding and germplasm banks

Ex-situ conservation measures would initiate captive maintenance programs for species that would otherwise become extinct due to climate change. They are not as preferable as the above options, but might be the last resort for the "no hopers" (Von Maltitz *et al.* 2006). Captive rearing, husbandry and propagation methods have been described for many animals and plants; and zoos, aquaria, botanic gardens and seed banks are well established. Studies have investigated the potential for captive breeding of species and of gene banks, but few with explicit links to climate change.

For some species, captive breeding has been successful, e.g. Scimitar-horned oryx, now considered extinct in the wild, persists in large numbers in captivity (Iyengar *et al.* 2007). However for other species, such as Arctic marine mammals, captive breeding as an adaptation option is largely unfeasible (Ragen, Huntington & Hovelsrud 2008) and should be seen as a last resort for populations approaching extinction, e.g. South African critically endangered riverine rabbit (*Bunolagus monticularis*) (Hughes *et al.* 2008). Previous non-climate related reviews of captive breeding have similarly suggested that this is a resource demanding and technically difficult activity, mainly restricted to vertebrates, and should be a last resort (Ayyad 2003), particularly given the low rates of success reported for many species, and the fact that it shifts attention away from *in situ* preservation of habitats (Hughes *et al.* 2008). Further, removal of all individuals into captivity would cause species to go extinct in the wild, with potentially severe consequences for the species' native ecosystem and their functioning. Another cause for concern is that captive breeding can reduce genetic diversity (Berry *et al.* 2008).

Genetic diversity might potentially be captured in banks storing germplasm, such as seeds, eggs and sperm. The maintenance of genetic seed banks could complement *in situ* measures to buffer against extinction threats from climate change and provide a source of germplasm for future restoration and research (Simpson & Wang 2007). Plants have commonly been stored in seed banks, and an objective of the CBD is that 60% of threatened plant species should be held in accessible ex situ collections (Target 8, Global Strategy for Plant Conservation 2006). The UK Millennium Seed Bank Project aims to have banked seed from 10% of the world's wild plant species by the end of the decade and Austria has maintained a network of genetic reserves distributed along environmental gradients (Geburek & Muller 2006). Maintaining genetic diversity of ecosystems is likely to be particularly important in maintaining resilience to climate change, and seed banks could contribute to this (Kleinschmit 2002). A recent study suggests that plant species endangered due to habitat destruction and climate change can be effectively and efficiently propagated *ex-situ* (Millner *et al.* 2008), and the creation of gene banks has been suggested as an adaptation strategy for oaks and pines in Mexico (Gomez-Mendoza & Arriaga 2007) and plant species in China (Li & Xia 2004), as a complement to habitat conservation. The inclusion of crop wild relatives in seed banks could also contribute to agricultural adaptation (Jarvis *et al.* 2008).

Captive breeding and germplasm banks require large resources for their maintenance and are therefore unlikely long-term strategies for more than a few species. Further, the ecosystems might become so altered that reintroduction of species back into the wild becomes unfeasible, consigning these species to become “living fossils” (Heinz 2008).

5.2.3 Genes

High levels of genetic diversity within populations are desirable to ensure adaptability. As genetic diversity is correlated with population size and diversity, adaptation should strive to maintain or create large populations. Further gene flow between populations might be desirable, but mixing could also swamp local adaptation and result in homogenisation (Gregory *et al.* 2006). The adaptation strategies outlined above for ecosystems and species with their advantage and disadvantages are likely to apply similarly to genes. The causes and consequences of the maintenance and loss of climate-related genetic diversity within populations are currently poorly understood and require further research (Jump & Penuelas 2005).

Actions in the conservation sector should by definition have a positive impact on biodiversity. However, conservation following “business as usual” under future climate change can have negative impacts (Hannah *et al.* 2002). Conservation management in the context of climate change will need to identify in the short term effective actions that can improve the abilities of ecosystems and species to accommodate and adapt to climate change in the medium and longer term, despite the many uncertainties that still exist and the lack of concrete information about the effects of different management actions (Heller & Zavaleta 2008). As a whole, the sector is likely to draw on a wide range of options including expansion and alteration of protected areas systems and changes to their management, enhancing the functional connectivity between ecosystems through the use of corridors, stepping stones and wildlife friendly management of the wider landscape, reducing the impacts of pressures not linked to climate change, and managing species directly to enhance their ability to persist and to shift their ranges in response to climate change. While most of these adaptation measures will benefit some species if carefully implemented, there is a danger that some will have secondary consequences affecting biodiversity negatively, e.g. invasive species due to translocation. Therefore, careful consideration is required to minimise potential negative consequences before adaptation measures are implemented. Enhancing the resilience of biodiversity to the impacts of climate change is likely to be important both for societal adaptation and for mitigation.

6 Synergies and trade-offs between adaptation and mitigation

Adaptation measures required will depend on the scale of the impacts. Adaptation is therefore closely related to mitigation, and some recognition of the synergies and trade-offs between adaptation and mitigation strategies is required (Ayers & Huq 2008). The IPCC 4AR reported that there was inadequate literature on the relationship between adaptation and mitigation policy (Adger *et al.* 2007) and this area is only recently beginning to be explored (Nyong, Adesina & Elasha 2007). In some cases, adaptation measures can contribute to mitigation, whereas in others they may run contrary to each other (Berry *et al.* 2008). It is important to recognise the areas in which trade-offs need to be made (Harper 2008), as well as to identify 'win win' solutions. It has been suggested that natural resource management is one of the areas with the greatest potential for achieving the objectives of both adaptation and mitigation, due to the major role that ecosystems play in the carbon cycle (as reviewed in the background documents for the first meeting of the Second AHTEG on Biodiversity and Climate Change) (Campbell *et al.* 2008)), and in underpinning adaptation strategies (Ravindranath 2007). Desertification, biodiversity and climate change are dealt as separate issues under the international convention, when in fact they all interact (Cowie, Schneider & Montanarella 2007; Eriksen *et al.* 2006).

REDD is commonly identified in the literature as a strategy with the potential to support both adaptation and mitigation, whilst providing significant biodiversity benefits (Locatelli *et al.* 2008; Murdiyarso *et al.* 2005; Nabuurs *et al.* 2007; Ravindranath 2007; Eliasch 2008; Nepstad *et al.* 2008; Righelato & Spracklen 2007). Soil and water conservation through good agricultural practice and agroforestry can reduce carbon loss and enhance soil organic matter to reduce the vulnerability to drought and flooding (Nyong *et al.* 2007; Ravindranath 2007; Verchot, V *et al.* 2007; Berry *et al.* 2008; Lal 2008; Rosenzweig & Tubiello 2007). Planting species mixtures can stabilize soil, reduce flooding, and improve the adaptive capacity of forest plantations in the long term (Berry *et al.* 2008), and mangrove plantations can build resilience to coastal storms and also sequester carbon (Ayers & Huq 2008).

It is clear that there are significant areas of overlap between adaptation and mitigation. However, there are also trade-offs to be made. Water resources can be directly impacted by forestry mitigation activities where appropriate species are not used (Betts 2007). Adaptation options in the water sector can involve draining wetlands, turning them into a net source of emissions (Mata & Budhooram 2007). This area would appear to require further research. Any adaptation option that involves the loss and degradation of natural ecosystems can result in green house gas emissions, and may be maladaptation in the long term.

7 Conclusion

Adaptation to climate change is a relatively new field, and the literature available in this area is limited. Very few adaptation strategies have actually been implemented, but those that have tend to rely on technological and engineering measures**.** The limited evidence to date suggests that although technological and structural adaptation measures will be required, biodiversity will also play a vital role in adaptation to climate change.

The evidence presented here suggests that ecosystem-based adaptation can be a cost-effective strategy to address the impacts of climate change, particularly in vulnerable areas where adaptive capacity is low. Indeed, many of the examples to date have been linked to community-based adaptation, where local communities that rely directly on natural resources can increase their adaptive capacity through good management of their natural resource base (Huq *et al.* 2005). The lack of cost-benefit analyses of the different adaptation options makes conclusions tentative and most available evidence is anecdotal or based on case studies. However, it is clear that coastal ecosystems can play a role in coastal protection and buffer the impacts of storms while maintaining fish supplies; natural wetlands and rivers are vital in water adaptation; and forests play a role in water regulation and soil conservation whilst maintaining livelihood options. Crop diversity and good agricultural practice is likely to play a large role in agricultural adaptation. This is not just important for the poor, but for society as a whole.

The term 'ecosystem-based adaptation', although it has been used here, can give the impression that adaptation based on biodiversity is completely separate from other more structural measures; and that adaptation strategies are either ecosystem-based or structural. In fact, optimal adaptation strategies often involve the incorporation of biodiversity into wider adaptation planning as a complement to, rather than an alternative to, structural measures. Indeed the importance of adopting an integrated approach that incorporates adaptation measures that are based on biodiversity is highlighted throughout the literature.

Furthermore, climate change impacts can be exacerbated by management practices, such as the development of seawalls, flood management and fire management, that do not consider other sectors such as biodiversity conservation and water resource management; this results in maladaptation in the longer term (World Bank 2008; Hulme 2005). In addition, the use of technology and infrastructure can 'lock in adaptation' to a specific impact, whereas the incorporation of 'soft' adaptation measures, including land use planning, natural resource management, and building social adaptive capacity, can allow for flexible responses (Kirshen *et al.* 2008; Koch *et al.* 2009; Matthews & Quesne 2008). Integration is required not just between biodiversity-based adaptation and technological measures, but also across different adaptation sectors, and will require significant institutional support.

Climate change is already having measurable impacts on ecosystems and on biodiversity more generally, and these are expected to grow. Adaptation in the biodiversity conservation sector is required, not just to achieve the conservation of biodiversity for its own sake, but to maintain the role of biodiversity in contributing to societal adaptation. Adaptation strategies in the conservation sector are still in the early stages of development. They include factoring climate change into protected area design, managing the wider landscape to ensure functional connectivity between habitats, and reducing other pressures on ecosystems. Careful consideration of adaptation options such as assisted migration is required, as actions to improve the conservation status of one species might have wider impacts on biodiversity. More guidance is required on how to build resilience to climate change in ecosystems and species, particularly in developing countries where many people are directly reliant upon their natural resources.

Increasing the resilience of ecosystems to climate change also supports their role in climate change mitigation. The linkages between mitigation and adaptation are only beginning to be explored, but it is clear that natural resource management is one of the areas with the greatest potential for synergies. It is also an area in which trade-offs can exist. Managing the trade-offs and promoting the synergies between adaptation and mitigation in the land use sector is likely to be important both in adaptation to climate change, and in limiting climate change to a level at which it is still possible to adapt.

Although we have separated this report into three sections, considering the role of biodiversity in societal adaptation, the impacts of adaptation strategies on biodiversity, and adaptation in the biodiversity conservation sector, it is clear that all three are interlinked. Ultimately, a broader perspective is required that focuses on how ecosystems can be managed and conserved in order to deliver ecosystem goods and services in a changing climate, within the context of overall adaptation policy.

The coverage of costs and benefit analyses across adaptation options is uneven, and further research is required in this area. There needs to be greater consideration of synergies and trade-offs in adaptation policy and planning, including improved understanding of the underpinning role of biodiversity, to avoid maladaptation and develop cost-effective responses to the impacts of climate change.

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