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DEVELOPMENT AND CLIMATE CHANGE

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All dollars are U.S. dollars unless otherwise indicated.

TABLE OF CONTENTS

Tables

Figures

Boxes

1. BACKGROUND

Climate change is expected to have major negative impacts on developing countries, but current estimates of the cost of measures to adapt to climate change are incomplete, crude, or entirely absent. A few global studies have been carried out in recent years (Oxfam 2007; Stern 2006; UNDP 2007; UNFCCC 2007; World Bank 2006). A program to develop national adaptation plans—established by UNFCCC—has been implemented in about 23 least-developed countries so far. Many other studies have been carried out within countries, and for specific sectors such as agriculture or water. But the economics of adaptation to climate change is a new research area, and no agreed methodology to assess overall costs has yet emerged. In addition, the effects of climate change depend importantly on national and subnational climate parameters—such as temperature variation over a day and by season, and the volume and timing of precipitation. These parameters have been developed at the global or broad regional levels, but there is much less confidence in estimates at the national level.

An understanding of the full array of adaptation options, including institutional and policy changes, is crucial to prioritize the most effective adaptation strategies. Countries need better estimates of the overall budget implications of implementing "climate resilient development," both to implement their national strategies and to inform discussions concerning possible international assistance. In order to develop estimates of the cost of adaptation at the national, regional, and global levels, a partnership has been formed between the World Bank and the governments of the Netherlands, the UK, and Switzerland. The World Bank is leading the technical aspects of the study, while the Netherlands, UK, and Switzerland have agreed to fund the analysis.

The overall study has two objectives. The first is to help decision makers in developing countries to better understand and assess the risks posed by climate change and to better design strategies to adapt to climate change. This will be achieved by carrying out case studies at the country level that identify costs, priorities, and sequencing to integrate adaptation measures into national development plans and budgets. The second objective is to develop a global estimate of adaptation costs to inform the international community's efforts, including UNFCCC and the Bali Action Plan; to provide access to adequate, predictable, and sustainable support; and to provide new, additional resources to help the most vulnerable developing countries meet adaptation costs. The study will proceed simultaneously with two parallel tracks: one at the country level and another at the global level based on global and regional modeling.

The global track will ensure the availability of an estimate of developing country and regional adaptation costs to contribute to the discussion on climate change leading up to the Copenhagen conference in late 2009. But the global track cannot identify the country-specific plans and actions that will be needed by each country; that is the purpose of the country case studies. The second objective of the global track is to develop the procedures that will be needed to generate aggregate adaptation costs based on the country case studies, once those results are available.

The overall study attempts to make a distinction between development and adaptation. Many developing countries are far behind in meeting the Millennium Development Goals and need a great deal of investment to meet the MDGs even if climate change were not occurring. This has been called the "development deficit." Adaptation costs are defined as the incremental costs imposed by climate change, in addition to, but not including, the costs of development. In practice, it is often hard to distinguish the two. The best adaptation measures may not always be "add-ons" to conventional development projects and programs. Many practitioners have said that good development is the best form of adaptation (Schelling 1992, echoed by the Stern report in 2006). Nevertheless, the study will keep to the distinction wherever possible.

This paper reports on a study for the global track on ecosystem services. The scope of this report is more narrow than the other sector reports. As will be described below, not all ecosystem services are addressed, and it was not possible to identify at the global level a cost of adaptation. Nevertheless, the threat to certain critical ecosystem services is identified, quantified to the extent possible, and examples of costs for potential adaptation measures are described.

1.1 ECOSYSTEM SERVICES IN PREVIOUS GLOBAL STUDIES OF THE COSTS OF ADAPTATION

The Millennium Ecosystem Assessment (2005) established a classification of ecosystems and ecosystem services that is now widely used. The overarching categories of ecosystem services include

- Provisioning services are goods that people obtain from ecosystems such as food, fuel, fiber, fresh water, and genetic resources.
- Regulating services include benefits people obtain from the regulation of ecosystem processes, including air quality maintenance, protection from natural hazards (floods, storms), climate regulation, erosion control, regulation of human diseases, and water purification.
- Cultural services include spiritual enrichment, recreation, education, and aesthetic experiences.
- Supporting services are services necessary for the production of all other ecosystem services such as primary production, production of oxygen, and soil formation.
- Biodiversity, though not explicitly identified as a separate ecosystem service in the initial report, has been identified as a separate service in subsequent reports that provide more detailed assessments of specific ecosystems, e.g., marine and coastal ecosystems (UNEP 2006).

The very broad scope of ecosystem services make them a part of everything humans use or do, either directly or indirectly. In the ecosystem services approach of the MA, ecosystems are not so much a unique sector like agriculture or infrastructure as they are a way of analyzing human activities in the context of the global environment, which makes life possible. The entire earth and all human activities are part of ecosystems of one sort or another, including human-dominated ecosystems such as urban areas. Provisioning services and cultural/recreational services are used directly, both as private goods and public goods. Regulating and supporting services are used indirectly, as inputs to the production of goods and services consumed by humans.

The first study on the global costs of adaptation by the World Bank (2006) was based largely on incremental costs to "climate-proof" investments in infrastructure and did not explicitly address ecosystems. UNFCCC (2007) took a more disaggregated approach with separate sector studies to estimate adaptation costs for infrastructure; water; agriculture, forestry and fisheries; coastal zones; and human health. Tourism and recreation were not explicitly addressed, but part of their adaptation costs were implicitly included in the infrastructure and coastal zone assessments. Some regional and country studies have considered tourism; for example, OECD (2008) addressed problems and possible adaptation measures for winter tourism and fishing tourism in Europe.

In the background documents for UNFCCC, a separate case study was done for the costs of adaptation for ecosystems, although these costs were not included in the final estimate. Ecosystems were not treated in the Millennium Ecosystem Assessment sense, but were defined very narrowly—the only ecosystem service considered was biodiversity. Adaptation was to be achieved by increasing the terrestrial and marine area under protection status to the target area established by IUCN, 10 percent of global land area. The target area for protection status is the amount considered necessary under current conditions, before climate change, not the additional area needed for adaptation to climate change. The incremental cost needed to adapt to climate change was not identified. Since the area currently under protection does not meet the minimum necessary for biodiversity protection, this estimate combines a "development deficit" as well as an adaptation cost.

Furthermore, it did not define "adequate" adaptation for conserving biodiversity under climate change, and it appears not to be possible to determine what the impact of this measure would be on biodiversity. Because of such concerns, it was omitted from the global costs of adaptation reported in UNFCCC (2007).

1.2 ECOSYSTEM SERVICES ADDRESSED IN THIS REPORT

The present study of the economics of adaptation to climate change follows the sector approach, with separate estimates of adaptation measures for infrastructure, water, agriculture, industrial forestry, fisheries, coastal zones, human health, and ecosystems. However, using the definition of ecosystem services developed by the Millennium Ecosystem Assessment (MA 2005), it is clear that most of the services are included in the sector studies either implicitly or explicitly. The sectors addressed in each study take place within ecosystems, and ecosystem services are critical to their functioning even if these services are not identified explicitly. Provisioning services are included explicitly in water, agriculture, industrial forestry, and fisheries sector studies. Regulating and supporting services are used indirectly for the production of goods and services in the sector studies; such as pollination as an input to agriculture, or watershed protection for water supply, hydropower, and agriculture. Although not addressed explicitly in sector studies, projections about the future of these sectors implicitly assume some level of these indirect services.

Because most ecosystem services have already been addressed, explicitly or implicitly, in the other sector studies for this report, they cannot be counted again here without double-counting. There are, however, a number of ecosystem services that have not been addressed, either explicitly or implicitly.

- Provisioning services: ecosystems provide a range of wild products (food, medicines, building materials, etc.) that are critical for livelihoods. Among all the ecosystems, forests and woodlands are the most important, providing wood fuels and non-wood forest products (NWFP). The use of wood fuels and NWFP, critical for the livelihoods of over 2 billion people in developing countries, has not been addressed. The sector study for forestry considers only the largest economic forest product—industrial timber—and does not include all the non-industrial products.
- Regulating services: a number of regulating services are not addressed, or only partly addressed, in the sector studies, such as the flood and storm protection services of wetlands. The sector study for coastal protection from sea-level rise and increased storms and flooding considered built-up and beach areas and measures to protect them through infrastructure construction (e.g., seawalls, dikes) or beach nourishment. Protection of coastal areas by wetlands and coastal forests, which were very important in certain areas in the 2004 tsunami in Asia (Bratz et al. 2006), was not addressed. Generally, all the global studies have focused more on "hard" adaptation measures rather than "soft" adaptation measures; for example, building dams and seawalls rather than rehabilitating natural systems like wetlands.
- Cultural services, tourism and recreation: the costs of maintaining coastal tourism infrastructure is implicitly part of the infrastructure study and the coastal study, but there are other aspects of tourism that have not been addressed; for example, the impact of coral bleaching and resulting death of coral on dive and snorkeling tourism.
- Biodiversity has not been discussed in any of the sector studies.

Within the limited scope of this report, it is not possible to address all these missing ecosystem services. However, we will consider two services:

- Wood fuels and NWFP
- Coastal protection services provided by mangroves

2. WOOD FUELS AND NON-WOOD FOREST PRODUCTS

At the global level, more than 2 billion people rely on biomass for energy, mostly in developing countries. This figure is expected to grow in absolute terms in all regions except China (Table 1).[1, 2] For many countries in Sub-Saharan Africa, Latin America, and Asia, biomass, mainly wood fuel, constitutes a major source of household energy, mainly used for cooking and heating. In Africa, where less than 10 percent of the population in rural areas has access to electricity, 80 percent of households rely on biomass to satisfy energy needs. But even in urban areas where access to electricity is much further advanced, many households use wood fuels—mainly charcoal—for cooking.

TABLE 1. PEOPLE RELYING ON TRADITIONAL BIOMASS FOR ENERGY, 2004 TO 2030 (MILLIONS)

	2004	*2030*
Sub-Saharan Africa	575	720
North Africa	4	5
India	740	782
China	480	394
Indonesia	156	180
Rest of Asia	489	561
Latin America & Caribbean	83	85
Total	**2528**	**2727**

Source: IEA 2006.
Note: Traditional biomass includes wood fuel, charcoal, other wood-derived products, crop residues, and animal dung.

Forests also provide non-wood forest products (NWFP), which are very important for many households in developing countries (See Box 1). NWFP comprise a highly diverse group of products, varying by country, that includes food products (wild game and hides, fruits, nuts, honey, vegetables), materials for construction and household implements (thatch for roofs, grasses for mats and baskets, wood for cooking utensils, etc.), medicines, gums, fodder for livestock, ornamental foliage, and many other products. Some of these products are used for subsistence and some are sold in markets, including international markets.

What is striking is the paucity of global data for non-industrial forest products, especially subsistence use (Seppala et al. 2009; Sunderlin et al. 2005; Arnold et al. 2003). As recently as 2009, the International Union of Forest Research Organizations published a very detailed report—*Adaptation of Forests and People to Climate Change* (Seppala et al. 2009)—that had no global figures for NWFP or wood fuels.

FAO publishes annual estimates of the volume of wood fuel and charcoal used in all countries, but no estimate of the value. There is no global estimate of NWFP. Many of these products are used for subsistence and are often poorly accounted for, if at all, in national statistics. To the extent that such products are traded internationally, the volume and value of such products are recorded. FAO reported over US$2 billion in global trade in NWFPs in 2002, mainly exports from industrialized

1 While people in developed countries also use wood fuel and harvest non-timber forest products, they are far less significant for household livelihoods. Given the scarcity of data, we focus on developing countries where populations are much more vulnerable.

2 Recent global price developments for energy have demonstrated that these forecasts are at best indicative and that future global energy price developments may change this picture quite drastically.

BOX 1. FOREST INCOME AND RURAL LIVELIHOODS

A meta-analysis (Vedeld et al. 2004), synthesizing 54 case studies, found that forest environmental income (wood fuel, NWFP, livestock grazing/fodder) contributed an average of US$678 (PPP-adjusted) to rural household income, accounting for 22 percent of household incomes. Dependence on forests was even greater for poorer households; forest incomes accounted for an average of 32 percent of income for poor and very poor households. Wood fuel and wild foods accounted for nearly 75 percent of the value. A more recent study found that in India forest resources accounted for 40 percent of income for households in the bottom two income quartiles (Narain et al. 2008). It is clear that for poor households, access to forest products is critical for survival.

Forest products contribute in several ways to rural livelihoods:

- Current consumption: forest products are a regular part of household consumption, either on a daily basis (e.g., wood fuel for cooking) or seasonal (e.g., fruits and vegetables). For many households in rural areas, forest products are essential to keep them from falling into poverty or more extreme poverty.
- Safety net: forest products are used to overcome shortfalls or loss of income, e.g., in a time of seasonal unemployment, before crop harvesting, or household emergencies.
- Pathway out of poverty: if income from forest products is sufficient, households may be able to escape poverty.

While the income from forest products accrues mostly to rural communities living in or adjacent to forests, they are not the only ones who rely on forests. Many urban households, who purchase these products, rely on wood fuel and charcoal as a relatively inexpensive source of energy. They can be purchased in very small amounts and can be used with simple, inexpensive equipment, as little as a few large stones. Charcoal is especially important because it is easier than wood to transport and to use. In Sub-Saharan African countries, several tens or even hundreds of thousands of mostly poor people rely on the charcoal trade for their livelihoods—either as charcoal producers, traders, transporters, or producers of charcoal stoves. Many urban households also rely on traditional medicines for healthcare. For poor urban households, the loss of these affordable forest products would be a serious hardship.

countries (FAO 2005, quoted in (Seppala et al. 2009)). But international trade in NWFPs is only a small part of total use. Because of the lack of data about NWFP, the rest of this section is concerned with wood fuels, the impact of climate change, and adaptation measures. Some observations about the implications for NWFPs will be included at the end of this section.

2.1 CURRENT AND PROJECTED USE OF WOOD FUEL

Wood fuel includes charcoal and other wood-derived fuels. The FAO database includes consumption of wood fuel and charcoal, reported separately, for each country; other wood-derived fuels are not included. Wood is consumed in the production of charcoal, so to estimate total wood-fuel use, charcoal must be converted to its wood-fuel equivalent. The conversion factor used in this report is 13.9 cubic meters of cut wood per ton of charcoal. This represents an average obtained from data for several Sub-Saharan African countries. It has to be acknowledged that conversion efficiencies can vary significantly by country and region and are probably lowest for Sub-Saharan African countries.

Table 2 shows the amount of wood fuel used by region in 2006, the most recent year for which comprehensive data are available, with projections by FAO to 2030.[3] There is considerable variation in the use of wood fuel across regions. Africa has the highest wood-fuel consumption, both in absolute numbers and per capita, using 0.63 cubic meters of wood fuel per capita annually. Even though East Asia and South Asia have the lowest use per capita, this should not disguise the fact that—especially in South Asia—a large share of the population—especially the urban and rural poor—rely on wood fuel to satisfy energy needs, notably for cooking and heating. Therefore, within each region, use of wood fuel can vary enormously; each region contains countries with very high and very low per capita wood-fuel use (see Figures 1–3).

On a global level, demand and supply of wood fuel is balanced (Seppala et al. 2009), but the global figure hides considerable imbalances at the country and subnational levels. For example, a study of wood-fuel availability in East Africa (Drigo 2005) shows vast areas with abundance, but also large areas with serious shortfalls in wood fuel (Figure 4).

3 Projections for 2050, the target year for the study, were not available.

TABLE 2. USE OF WOOD FUEL IN 2006 AND PROJECTIONS TO 2030

	2006			*2030*		
Region	*Wood fuel (million m³)*	*Population (millions)*	*Per capita wood fuel (m³/person)*	*Wood fuel (million m³)*	*Population (millions)*	*Per capita wood fuel (m³/person)*
South Asia	383	1,516	0.25	373	2,027	0.18
Southeast Asia	186	564	0.33	113	708	0.16
East Asia	213	1,531	0.14	152	1,654	0.09
Africa	589	940	0.63	1,185	1,513	0.78
South America	241	453	0.53	400	577	0.69
Rest of the World	258	1,556	0.17	328	1,788	0.18
Total	1,869	6,559	0.28	2,552	8,266	0.31

Source: FAO 2009 provided country-level data on use of fuel wood and charcoal in 2006.
Broadhead et al. (2001) as quoted in Arnold et al. (2003), provided regional projections for charcoal and fuel wood for 2030.
World Bank (2009) provided population in 2030.
Note: Wood-fuel use reported separately for fuel wood and charcoal. Authors estimated total wood fuel by converting charcoal to fuel-wood equivalent.

Typically, as income grows, the use of wood fuel declines, as households substitute fossil fuels, which are often easier and cleaner to use, for wood fuel. However, even with income growth, most developing countries will continue to rely heavily on wood fuel (FAO 2008; International Energy Agency 2006). On a per capita basis, wood-fuel use in Africa and Latin America is projected to increase substantially by 2030.

FIGURE 1. WOOD FUELS, 2006, ASIA *(CUBIC METERS PER CAPITA)*

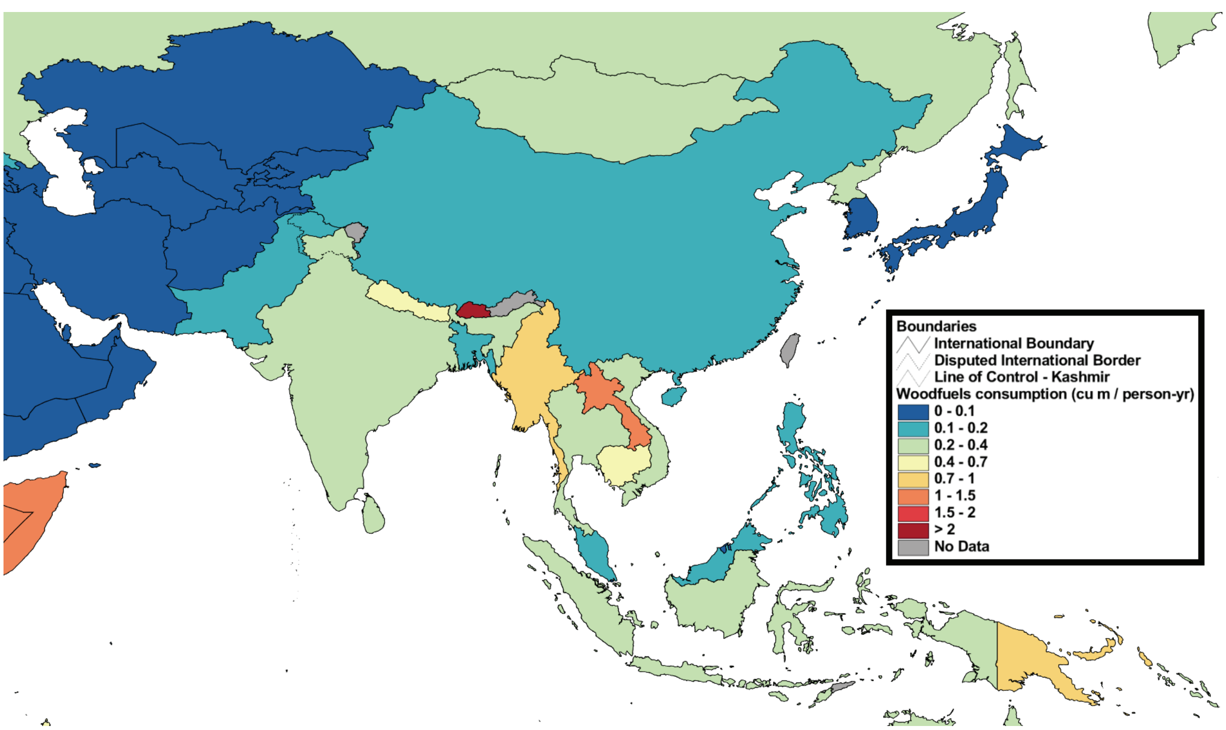
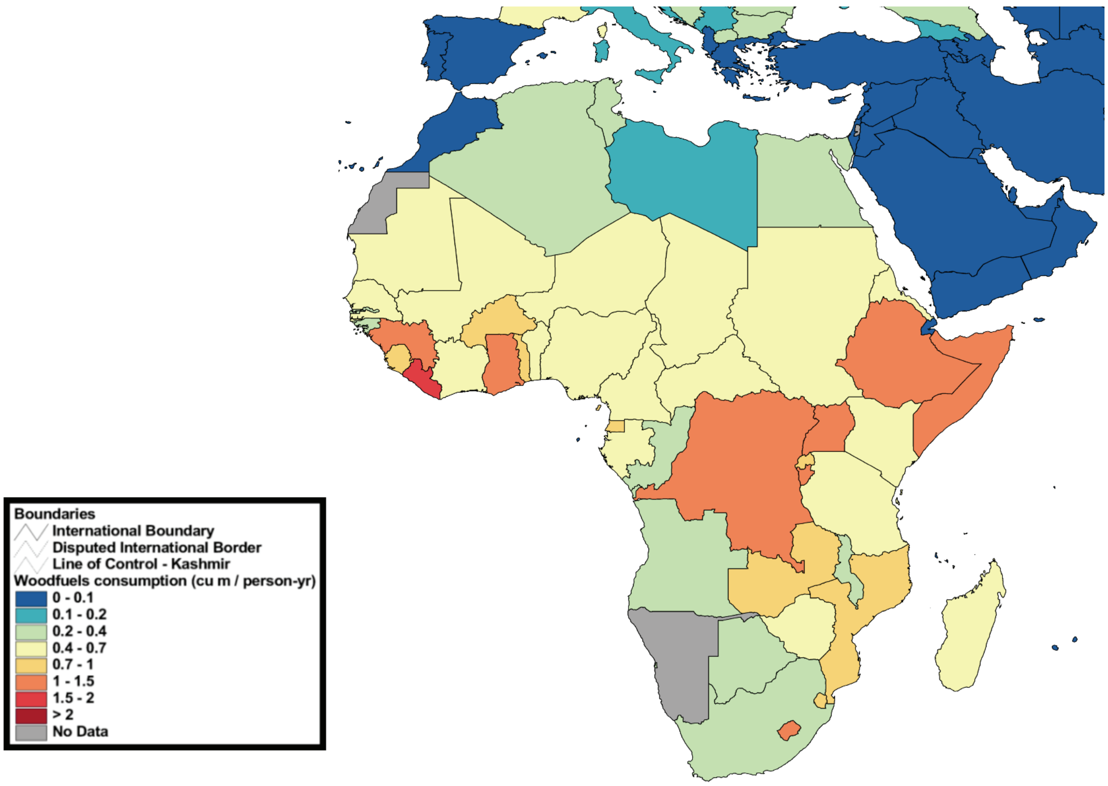


FIGURE 2. WOOD FUELS, 2006, AFRICA *(CUBIC METERS PER CAPITA)*



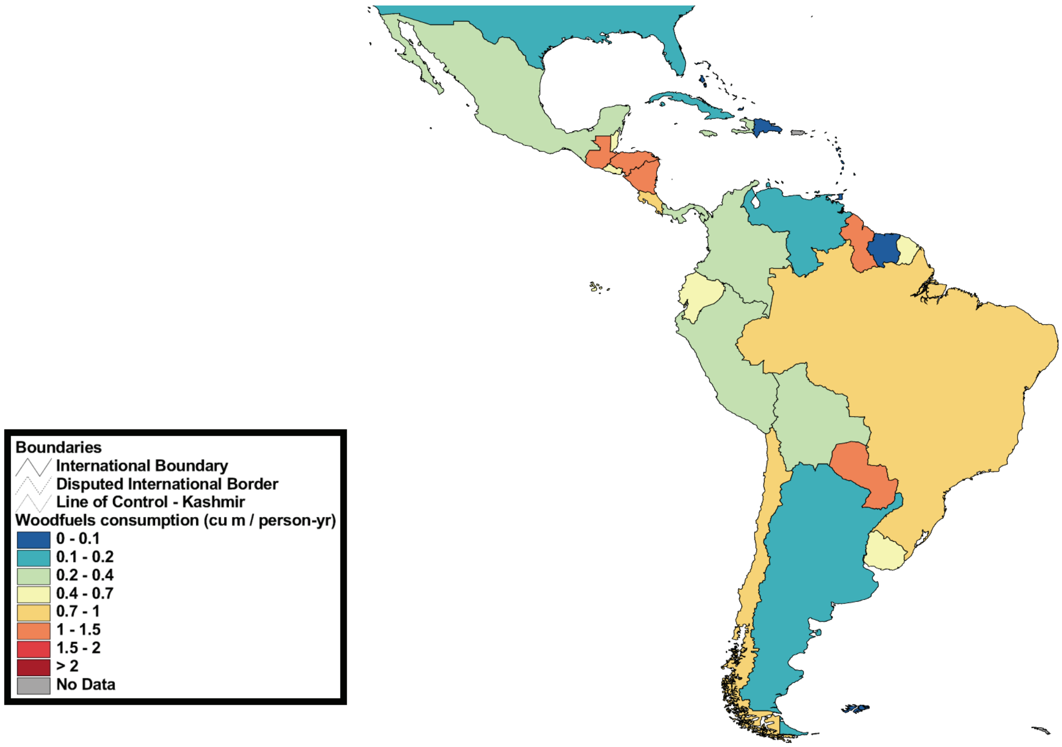
2.2 IMPACT OF CLIMATE CHANGE ON FOREST NET PRIMARY PRODUCTIVITY

There are many factors that will affect the availability of wood fuel and NWFP in the future. This case study considers only factors related to climate change that directly affect forest productivity—temperature, precipitation and increased atmospheric CO_2 concentration—and draws on the available literature to project the impact. We use the same projections used by Sedjo (2010) for the industrial forest case study—i.e., those developed by Sohngen et al. (2001)—and will not repeat the description of the model, other than to note that this model is widely accepted and cited by, for example, Easterling (2007) and Seppala (2009).

Sohngen et al. used a time horizon of 2145 for their estimates; this was adjusted by Sedjo for 2050, the time horizon of this study. The resulting estimates, reported in Sedjo (2010), are hereafter referred to as Sohngen/Sedjo projections. Sohngen et al. (2001) used the BIOME3 ecological model of Haxeltine and Prentice (1996) together with two general circulation models—UIUC and Hamburg. The projections are concerned with future production of industrial timber and are based mainly on projections of changes in forest net primary productivity, a measure of the rate of plant growth. The changes in NPP apply to all forests, so these projections provide a reasonable indication, at the regional level, of the direct impact of climate change on natural forests that supply wood fuels and NWFP.

The Sohngen/Sedjo projections indicate NPP will increase under climate change in all developing regions (low- to mid-latitudes), at least through 2050 (Table 3). Forest productivity is projected to increase from a low of 4–5 percent in Africa and Asia-Pacific to as much as 22 percent in India, depending on the model. Little is known about the potential impact of climate change on NWFP

FIGURE 3. WOOD FUELS, 2006, LATIN AMERICA AND THE CARIBBEAN *(CUBIC METERS PER CAPITA)*



(Easterling 2007; Seppala 2009). It is not clear that circumstances that increase NPP for trees will also increase NWFP. Impacts are likely to be highly site-specific.

2.3 ADAPTATION MEASURES FOR FORESTRY

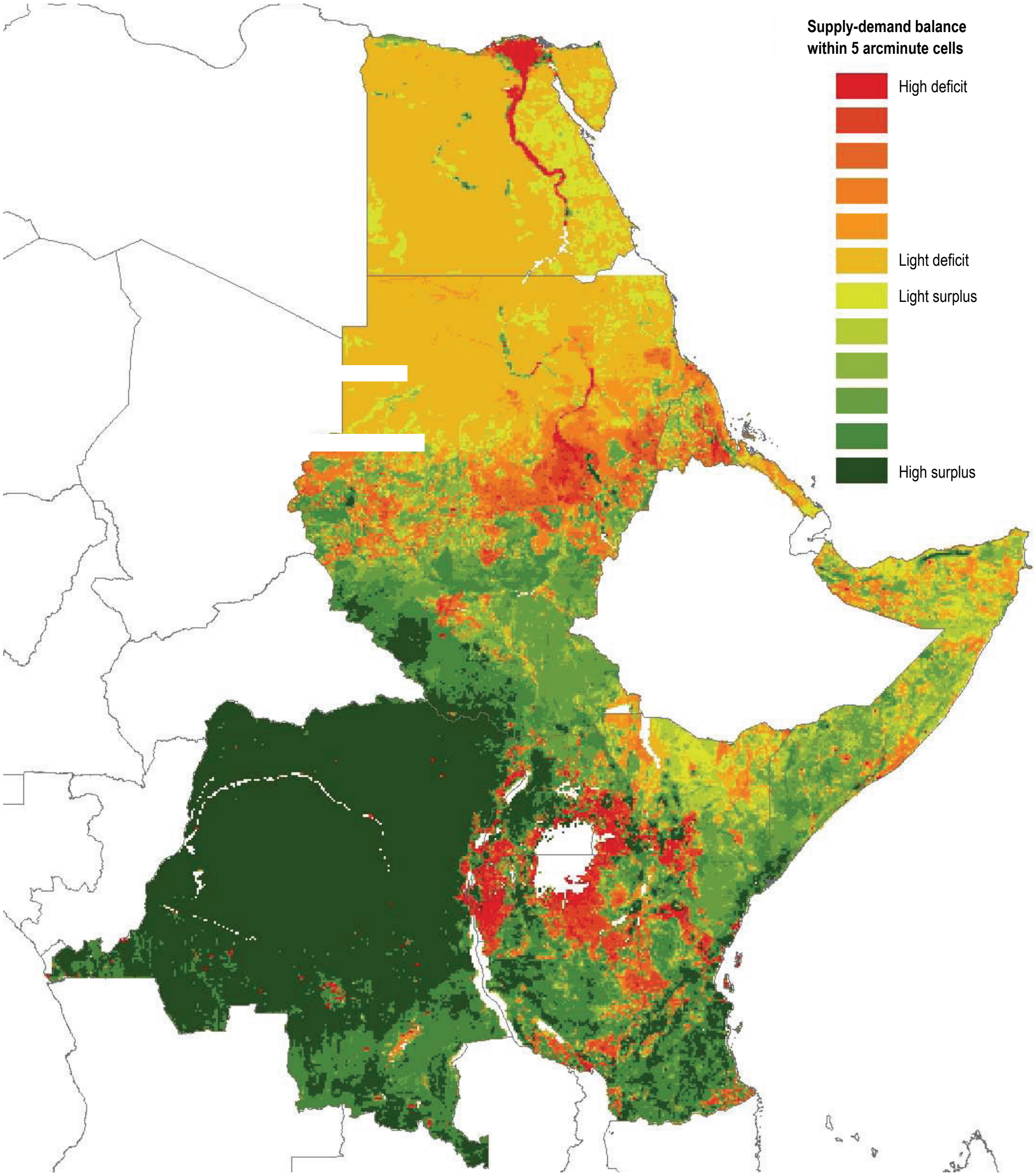
Based on projections of increased forest NPP, it would appear that no adaptation measures are needed for the provision of wood fuels in developing countries. However, there are ways in which climate change may indirectly affect forests that have not been quantified and work in the opposite direction: in some regions, climate change may result in increased fires, pest infestation, and disease. Furthermore, climate change may trigger population migration and increased pressure for conversion of forests to agricultural land. None of these factors have been considered in this assessment.

TABLE 3. PERCENTAGE CHANGE IN REGIONAL TIMBER PRODUCTION TO THE YEAR 2050

Region	*Hamburg 1995–2050*	*UIUC 1995–2050*
High-Latitude Forests		
North America	(1)	(2)
Europe	6	11
Former Soviet Union	7	3
China	12	11
Oceania	(3)	13
Low- to Mid-Latitude Forests		
South America	19	10
India	22	14
Asia-Pacific	10	4
Africa	14	5
Total All Forests	6	5

Source: Adapted from Sohngen et al.(2001) by Sedjo (2010). The results for the period 1995–2045 from Sohngen et al. were straight-line extended to 2050.

FIGURE 4. WOOD-FUEL SURPLUS AND DEFICIT IN EAST AFRICA



Source: Reproduced from Drigo (2005).

Within each region, there is also likely to be significant variation in the impact of and response to climate change. Sub-Saharan Africa, for example, includes vastly different countries. Some have tropical climates with heavy rainfall and dense forests; others are very arid and covered mostly by savannah woodlands. Averaging over the region, forest NPP in Africa is projected to increase, but in semi-arid and arid regions, productivity could decline substantially (Seppala et al. 2009).

Furthermore, the dependence of rural communities on forests also varies among countries and within a country. While the average contribution to household income from forests was estimated at 22 percent (Box 1), communities who make their homes within forests are entirely dependent on forests for their livelihoods and have little capacity to adapt to changes. Decreases in rainfall, and increasing occurrence and severity of droughts can have a devastating impact on these communities and their forests. Adaptation measures for such communities have not been considered in this report. A recent report on adaptation of forests (IUFRO 2009) stressed the importance of social rather than technical adaptation measures—flexible management and new modes of governance.

3. MANGROVE FORESTS AND COASTAL PROTECTION SERVICES

Adaptation to climate change will require living with sea-level rise and increased storm surges in many coastal areas. Coastal protection from storm surge and flooding is partly provided by built infrastructure, addressed by the Coastal sector study (Nicholls e 2010). Mangrove forests are a form of natural infrastructure that also provide coastal protection in tropical regions. This section describes the extent of mangrove forests, how mangroves will be affected by climate change, the human resources at risk due to loss of coastal protection from mangroves, and the potential for adaptation.

Mangroves provide many ecosystem services. They provide goods that contribute to livelihoods (food, timber, wood fuel, medicine) and habitat and nurseries for fish and other wildlife. They maintain water quality and protect coral reefs by trapping sediment, nutrients and contaminants; sediment trapping also protects coasts from erosion.

Mangroves also provide storm protection by reducing the flow of water and absorbing wave energy. The importance of mangroves was demonstrated by the Asian tsunami in 2004. Coastal areas with good mangrove forests suffered far less damage and loss of life than adjacent areas without mangroves (Bratz et al. 2006; Das and Vincent 2009; Forbes and Broadhead 2007; Kathiseran and Rajendran 2005; Vermaat and Thampanya 2006). A meta-analysis estimated the mean annual value of services provided by mangrove forests at roughly $400/hectare (Brander et al. 2006). However, high population pressure and economic development have resulted in significant loss of mangroves over recent decades in all regions (Table 4).

Mangroves are salt-tolerant forests at the interface between terrestrial and marine communities in tropical and subtropical regions. They receive water from the ocean with the tides as well as freshwater, which carries sediment and nutrients from upland rivers. Their aerial root system must be exposed to air for part of the day. Climate change will result in the loss of mangroves if sea-level rise is sufficient to cut off the flow of fresh water and nutrients and drown the roots.

Historically, mangroves are very dynamic; they have been subject to near continuous disturbance over the past few thousand years, showing considerable capacity to adapt to fluctuations in sea-level rise (Alongi 2008; Erwin 2009; Gilman et al.). Adaptation depends on the availability of suitable land for natural migration, a

TABLE 4. AREA WITH MANGROVES BY REGION, 1980 TO 2005 (*THOUSAND HECTARES*)

	1980	*1990*	*2000*	*2005*	*Change, 1980 to 2005 (%)*
Africa	3,670	3,428	3,218	3,160	–14
Asia	7,769	6,741	6,163	5,858	–25
Oceania	2,181	2,090	2,012	1,972	–10
North & Central America	2,951	2,592	2,352	2,263	–23
South America	2,222	2,073	1,996	1,978	–11
Total	18,794	16,925	15,740	15,231	–19

Source: FAO 2007.

continued supply of sediment and nutrients from freshwater inflows, and a rate of sea-level rise that is not greater than the rate at which mangroves can migrate.

3.1 ASSESSING THE IMPACT OF CLIMATE CHANGE ON MANGROVES

There have been a few studies of the impact of climate change and sea-level rise on mangroves (discussed in Alongi 2008). These range from a high of 30 percent of all wetlands (Solomon et al. 2007) to more moderate figures for specific areas, such as a 10–20 percent loss of mangroves in Pacific Islands (Gilman et al. 2008; Gilman et al. 2006). These studies did not quantify the human resources at risk from loss of mangroves, or costs of adaptation measures.

To assess the current level of coastal protection provided by mangroves and the potential for mangroves to adapt to climate change by 2050, we use information from two global GIS databases, DIVA and a database of world mangrove cover provided by UNEP-WCMC. The DIVA database contains information about the length of the world's coastline and various characteristics associated with each coastal segment. For this report, the characteristics of interest include the presence of mangrove wetlands, wetland migratory potential (explained below), and the population and GDP for 2000.

Mangrove coastline. The DIVA database includes information about the total area of mangroves in each coastal segment, but does not indicate the length of the mangroves along the coast. The mangroves may stretch along the entire length of the coastal segment or only a small portion. The WCMC database includes polygons showing the exact location, size, and shape of the mangroves. The WCMC and DIVA databases were combined to estimate the actual length of mangrove coastline within each DIVA coastal segment.

Human resources at risk. Information from DIVA indicates the human resources in coastal areas—population and GDP for 2000. No projections were made of population or GDP for 2050 in coastal zones; analysis of human resources protected by mangroves uses baseline data. Within a coastal zone, the number of people and GDP that are at risk under climate change and SLR, where mangroves may provide some protection, depend on the inundation area resulting from storm surges. The inundation zone for a 1-meter sea level rise and increase in frequency and intensity of storms was calculated using data and methods described in Dasgupta et al. (2009) and summarized in Box 2.[4]

Response of mangroves to SLR. To estimate the impact of SLR on mangroves and the potential for adaptation, we use another characteristic in the DIVA database, wetland migratory potential (WMP). WMP indicates the potential for wetlands, including mangroves, to migrate landward in response to a 1-meter rise in sea level. The migratory potential is based on a few geophysical characteristics of the coastline: coastal type, topography, tidal range, and other information when available (e.g., whether mangroves are associated with an island or mainland coast), as described in Hoozemans et al. (1993). The migratory potential of mangroves depends on a wide range of additional factors that are site-specific and highly variable; for mangroves, this includes such factors as the continued flow of sediment and nutrients from inland stream. Such detailed information was not available on a global scale.

Five possible responses to SLR, or categories of wetland migratory potential, were defined for the DIVA database:

1. No, or hardly any change
2. A retreat of the coastline, combined with inland migration of coastal ecosystems
3. A retreat of the coastline without the possibility of inland migration due to topography (e.g., coastlines with relatively high relief)
4. A possible retreat of the coastline but increase of flooding area behind the coastline ("ponding")
5. Total loss of the coastal ecosystem (Hoozmans et al. 1993).

In the DIVA database, no mangroves occur in areas with the most extreme responses, WMP 1 or WMP 5 (other wetlands may fall in these categories). If mangroves can migrate, WMP category 2, then they can continue to provide coastal protection services. Mangroves in these areas may survive in their current location to the extent

4 Sea-level rise may not reach 1 meter by 2050, but this was the smallest unit of SLR for which the database can provide figures.

BOX 2. ESTIMATING STORM-SURGE ZONES AND HUMAN RESOURCES AT RISK

Storm surge zones are locations that would be inundated by a given wave height, assuming the SRTM value represents ground elevation and there are no coastal protection measures. In the calculation of storm surges (wave heights or extreme sea levels), we follow the method outlined by Nicholls (2008) where future storm surges are calculated as follows:

Future storm surge = S100 + SLR + (UPLIFT * 100 yr) / 1000 + SUB + S100 * x

where:

S100	= 1-in-100-year surge height (m)
SLR	= sea-level rise (1 m)
UPLIFT	= continental uplift/subsidence in mm/yr
SUB	= 0.5 m (applies to deltas only)
x	= 0.1, or increase of 10%, applied only in coastal areas currently prone to cyclone/hurricane.

We apply the wave height calculated for the coastline segment closest to a drainage basin outlet to inland areas within that basin. We also included a distance decay factor of 0.3 m per 1 km distance from the coastline, in estimating wave height for inland cells.

Source: Based on Dasgupta et al. (2009).

that natural migration or sediment accretion keeps pace with sea-level rise (Alongi 2008). Mangroves in WMP category 3 cannot migrate, and the human resources associated with them will lose their protection. Mangroves in WMP category 4 are at great risk, but may survive, depending on the effect of flooding behind the coastline. If the flooding is severe enough and persists long enough to seriously disrupt the flow of freshwater and nutrients to mangroves, the mangroves will be severely degraded and may die, putting at risk the population currently protected by them.

Mangroves extend for nearly 37,000 km, accounting for 13 percent of coastline in developing regions, ranging from a low of 4 percent of the coastline in the Middle East and North Africa to a high of 21 percent in Sub-Saharan Africa (Table 5). The longest extent of mangrove coastline occurs in East Asia and the Pacific and Latin America, which, together, account for about two-thirds of mangroves worldwide. Under SLR, the inundation zone for mangrove coastal areas is inhabited by 176 million people, generating GDP of US$418 billion, with an average per capita income of US$2,381. These human resources, partially protected by mangroves, are potentially at risk from a 1-meter SLR and increased storm surge.

Across all developing regions, 69 percent of the mangrove coastline falls under WMP category 2, where there is a potential to maintain coastal protection by migration of mangroves with a 1-meter sea level rise (Table 5, Figure 5). These mangrove coasts support a significant share of population and economic activity in coastal areas, 97 million people (55 percent) and GDP of US$189 billion (45 percent). Another 31 percent of mangroves falls into categories 3 and 4, in which climate change will seriously compromise the viability of mangroves and the coastal protection services they provide.

Category 3 mangroves account for the only 9 percent of mangrove coastline, but 28 percent of the population and 41 percent of GDP associated with mangroves. Survival of mangroves and continued coastal protection is possible, but at risk depending on local conditions. Category 2 mangroves account for the remaining 22 percent of mangrove coastline. These mangroves are the most vulnerable to SLR and are likely to be lost, increasing exposure to damage from storm surge to 29 million people and GDP of US$56 billion.

The vulnerability of mangroves varies a great deal by region and by country. In the Middle East and North Africa, the region with the least mangrove coastline, only 15 percent of mangroves have the potential to migrate and survive, while 85 percent will be lost or at serious risk. By contrast, in Sub-Saharan Africa, 78 percent of mangroves are in WMP category 2, with

TABLE 5. POTENTIAL FOR MANGROVES IN DEVELOPING COUNTRIES TO MIGRATE IN RESPONSE TO SEA-LEVEL RISE

	WMP	Total coast-line (km)	Coastline with mangrove (km)	Coastline with mangrove	Mangrove coastline by WMP	Resources at risk: Population ('000)	Resources at risk: GDP ('000 USD)	Resources at risk: GDP per capita
East Asia and Pacific	2	53,832	9,240	17%	72%	50,282	138,115,190	2,747
	3	41,238	3,028	7%	24%	16,369	32,676,600	1,996
	4	7,664	538	7%	4%	27,309	107,175,838	3,925
	Total	102,734	12,806	12%	100%	93,961	277,967,628	2,958
Latin America and the Caribbean	2	61,643	8,671	14%	64%	6,979	27,527,516	3,944
	3	25,187	2,889	11%	21%	1,631	7,284,711	4,468
	4	11,411	1,981	17%	15%	2,998	16,856,432	5,622
	Total	98,240	13,541	14%	100%	11,608	51,668,659	4,451
Middle East and North Africa	2	1,398	131	9%	15%	80	136,035	1,705
	3	13,329	717	5%	83%	1,447	9,220,504	6,373
	4	7,764	19	0.2%	2%	8,756	41,887,176	4,784
	Total	22,491	866	4%	100%	10,283	51,243,715	4,983
South Asia	2	6,885	1,681	24%	69%	33,686	20,764,983	616
	3	3,085	390	13%	16%	6,915	4,353,492	630
	4	3,832	349	9%	14%	6,542	5,261,091	804
	Total	13,803	2,421	18%	100%	47,142	30,379,566	644
Sub-Saharan Africa	2	17,490	5,379	31%	78%	6,181	2,818,601	456
	3	10,252	1,095	11%	16%	2,511	1,970,184	785
	4	5,676	416	7%	6%	3,829	1,934,048	505
	Total	33,419	6,890	21%	100%	12,520	6,722,833	537
World	2	141,249	25,102	18%	69%	97,207	189,362,325	1,948
	3	93,092	8,120	9%	22%	28,872	55,505,491	1,922
	4	36,346	3,303	9%	9%	49,435	173,114,585	3,502
	Total	270,687	36,525	13%	100%	175,514	417,982,401	2,381

Source: Calculations described in the text.
WMP: Wetland migratory potential, described in the text.

great potential for migration. In many regions, the per capita GDP is higher in areas where mangroves are likely to be lost, compared to areas where mangroves have the capacity to migrate.

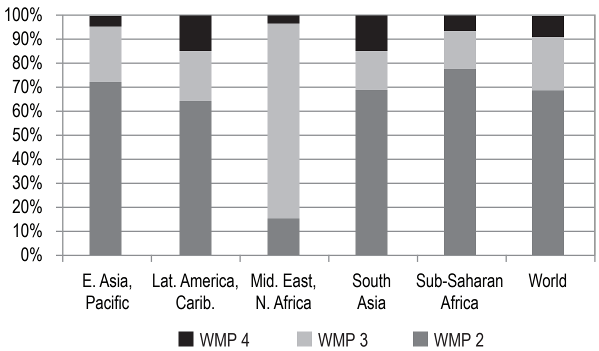
3.2 LIMITATIONS OF THE APPROACH

There are several major limitations to this approach; some lead to an overestimation of the coastal protection service, while others lead to an underestimation.

Factors that overestimate coastal protection:

- The mangrove database shows the extent and shape of the mangrove area, but does not indicate the status of the mangroves, e.g., patchiness, health, size of trees. Studies have shown that specific characteristics of mangroves are important for protection from storm surge. For example, if stands are not dense enough, they provide insufficient resistance to wave energy, but if the stand is too dense, waves may simply pass over (Bratz et al. 2006).

FIGURE 5. POTENTIAL FOR MIGRATION OF MANGROVES IN RESPONSE TO SEA-LEVEL RISE



Source: Table 5.
Note: WMP = wetland migratory potential as defined in the text.
WMP 2: inland migration is possible
WMP 3: inland migration of mangroves is not possible
WMP 4: inland migration may be possible, but with substantial increased flooding which threatens the viability of mangroves

- The mangrove database from WCMC is for 1997; data for 2007 will only be available in 2010. In some countries there has been significant loss of mangroves since 1997, so use of 1997 data will tend to overestimate the current levels of coastal defense. FAO (2007) indicates that globally only 3 percent of mangroves were lost between 2000 and 2005, so the 1997 data may be reasonably accurate at the regional level. But the loss of mangroves may be much larger in some countries.

Factors that underestimate coastal protection and resources at risk:

- Due to lack of data, the analysis does not include some small-island nations in Africa, Asia and the Pacific, and Latin America.

The other major limitation of this approach is that the potential for migration is only the first step toward understanding whether mangroves will actually migrate or not. Mangroves are already under severe pressure from conversion for aquaculture and tourism, overcutting, pollution, and other factors. Mangroves have been lost in many areas and are severely degraded in others. Many mangrove forests may not survive to 2050, regardless of the impact of climate change. For those forests that do survive, demographic, economic and other factors may block migration, even where the ecological conditions would make it possible. Coastal areas are the most densely populated parts of the globe, with many large, rapidly expanding urban areas; competition for space is fierce. Preserving and cultivating mangroves as a source of coastal defense will require addressing competing land uses, which is not possible in this report.

3.3 ADAPTATION MEASURES FOR MANGROVES

Adaptation measures to maintain the protection services of mangroves from the impact of climate change can take the form of (a) measures to support migration of mangroves where feasible, including afforestation, replanting, and rehabilitation of mangroves in appropriate areas; (b) substitution of "hard" infrastructure for mangroves; (c) combinations of mangrove forests and coastal embankments; or (d) migration of population and economic activities out of areas subject to storm surge and flooding. We will discuss the opportunities for supporting mangrove forests, either through migration or afforestation for use in combination with coastal embankments.

Mangroves in areas with the potential for migration may migrate naturally in response to sea-level rise if they are not blocked by other land uses, and sea-level rise is not faster than the natural migration rate. In other areas, intervention may be necessary. There have been many successful attempts to plant or rehabilitate mangroves in Asia and East Africa, including a large-scale effort in many countries affected by the 2004 tsunami (UNEP-WCMC 2006). Reviewing efforts in the Philippines, Primavera and Esteban (2008) found mixed results. Many afforestation or restoration and rehabilitation efforts failed because of inappropriate species and poor site selection. Mangroves were often planted in lower intertidal or subtidal zones, where mangroves do not naturally occur, because more suitable land was not available. With competing uses for coastal land, it will be difficult to find suitable land for mangroves as sea-level rises.

The costs of afforestation and replanting mangroves can vary enormously: Primavera and Esteban (2008) report average planting costs in the Philippines of over $500/hectare. This does not include the costs of purchasing land, where necessary. The Ramsar Secretariat, quoted in Gilman and Ellison (2007), reported a range of costs per hectare from US$225 to US$216,000, depending on the amount of rehabilitation needed.

One opportunity is the rehabilitation of abandoned aquaculture sites (if they are in areas identified as WMP 2). Over the past few decades, large areas of mangrove forests, especially in Asia, were converted for aquaculture, mainly shrimp farming. Many of these farming operations were abandoned after about five years due to disease and loss of profitability; the operators moved onto new sites (Barbie, 2009). Abandoned shrimp ponds are good sites for restoring mangroves because they are natural mangrove habitat with all the conditions necessary for mangroves to thrive. However, abandoned shrimp ponds are highly degraded and cannot be used for any other purpose because the soil has become very acidic, compacted, and of poor quality (Wolanski 2006). Mangroves will not naturally re-colonize these areas until the land is rehabilitated, and rehabilitation can be expensive. Barbier (2009) reported costs of US$8,812–$9,318 per hectare for rehabilitation, replanting, and maintaining mangrove seedlings. However, the benefits from restoration were significantly higher than the costs.

Another approach to coastal protection combines afforestation with mangroves and “hard” infrastructure, planting mangroves in front of an embankment. Mangroves can be relatively inexpensive to plant, provide additional benefits, and reduce the necessary height of the embankment as well as its maintenance costs (Tri et al. 1998). However, it is important to design the forest correctly for specific sites because there can be great variation in the protection provided by forests with different characteristics, e.g., width (Forbes and Broadhead 2008) and location (Box 3).

Even in areas with the natural potential for mangrove migration, there will be enormous variation across countries and within countries in the efficiency of using mangrove forests as “natural infrastructure” to protect coastal communities against storms and flooding. Where densely settled urban areas compete with mangroves for coastal land, it may be more efficient to use built infrastructure. Mangrove areas that meet both natural conditions as well as socioeconomic conditions for migration of mangroves, or use in combination with built infrastructure can only be identified at the country level.

For mangrove areas without the potential for migration, alternative measures will be needed to deal with increased vulnerability to storms and flooding, either built infrastructure or migration of population. The costs of these measures are beyond the scope of this study.

BOX 3. MANGROVE AFFORESTATION AND COASTAL PROTECTION IN BANGLADESH: THE IMPORTANCE OF SITING

A study to design the optimal combination of mangrove forest size and polder height was carried out for Hatia island in Bangladesh, an island that is often hit by cyclones, including the record 1970 cyclone. The study used simulation modeling to (a) identify the relationship between storm-surge height and forest parameters such as species, density, tree girth and forest width; and (b) based on this information, to determine the necessary forest area for a given height of embankment.

The authors derived the function showing the relationship between surge height and forest width up to 600 meters wide for different parts of the island. The study found that storm-surge attenuation varied not only by forest width, but also by location on the island. At the southern end of Hatia island, a mangrove forest 600m wide reduced the surge height by 0.45m, from about 6.20 m to 5.75m. For forest width of 133 m, surge height was reduced by 0.18m. However, no appreciable (>0.1 m) reduction in surge height was obtained by mangroves at the south-eastern or southwestern sides of the island. The results indicate that mangroves be used in combination with “hard” infrastructure, but that forest site as well as width must be planned carefully because site-specific characteristics greatly influence the extent of storm protection.

Source: Institute for Water Management 2000.

4. CONCLUSION

Regarding wood fuels and NWFP, the impact of climate change at the regional level does not appear to reduce forest productivity directly, implying that there are no serious adaptation costs. However, as explained in section 2, this conclusion must be viewed with caution because there is great variation among countries and within countries in the supply-demand balance of wood fuels, and in the degree of dependence on forest products by different households. It is likely that the relative surplus that may occur in some countries or some areas of a country will not compensate for the declining forest resources in other areas. This is especially true for subsistence use, for which proximity to forests is essential. There are many case studies of household dependence on forest products, but there is insufficient information to estimate the dependence at the regional and global levels. This is further complicated by the uncertainty regarding the impact of climate change at the subnational level.

Regarding coastal protection provided by mangrove forests, there is great potential for adaptation by natural or assisted migration, and geological evidence shows that mangroves have responded this way to sea-level rise in the past. Only about 20 percent of mangroves are likely to be lost due to sea-level rise; the rest may migrate if there are no other land uses blocking them. The costs of intervening to assist this process are not substantial, but can vary a great deal. There has been a lot of experience with replanting and rehabilitating mangroves, so mistakes that result in failure, common in the past, can be avoided. The major obstacle will be with competing land uses, as well as existing pressure on mangrove forests from overharvesting, pollution, and clearing for development. Even where mangroves survive the impacts of climate change, they do not provide complete protection from storms and flooding. The residual impact of climate change has not been estimated.

Serious gaps in the coverage of ecosystem services remain, notably with regard to biodiversity. However, it is not at all clear from the biological perspective what adaptation measures are necessary and effective for biodiversity. Some ecosystems and their unique flora and fauna will be lost; others may survive if species can migrate. It is possible that designing barrier-free corridors to allow natural migration can help promote adaptation for some species.[5] The studies of adaptation costs at the country level can carry this work forward, going into more detail for the ecosystem services covered in this study (coastal protection from natural infrastructure and non-industrial forest products) and addressing the missing ecosystem services.

The oceans have been particularly neglected in adaptation studies. The fisheries sector addresses some aspects of ocean ecosystems, but only those directly related to fisheries. Oceans play an important and complex role in regulating many fundamental processes on land and sea. Mangrove forests were discussed, but coral reefs, seagrass beds, and kelp forests are also important. There is relatively little information about the impact of climate change on ocean ecosystems and appropriate adaptation measures. Country case studies cannot solve this problem, as ocean ecosystems cut across national boundaries and vast areas are common property.

5 Such an approach is being considered in Germany (OECD 2008).

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