6 Carbon Sequestration, Land Degradation and Water

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Introduction

Land degradation and carbon sequestration

Human activities have profoundly affected many global biogeochemical cycles. The global carbon cycle has received the most attention in recent years as it has become clear that increased levels of CO_2 and other greenhouse gases in the atmosphere, primarily due to human activities, are causing changes to our climate at an increasingly rapid rate (IPCC, 1996, 2001). Land-use change, such as deforestation and agricultural expansion, has reduced terrestrial carbon stocks and has made major contributions to increases in atmospheric greenhouse gases. While CO_2 emissions from fossil fuel consumption now account for 75% of CO_2 annual emissions (Malhi *et al.*, 2002), the overall contribution derived from fossil fuel combustion only surpassed the proportion contributed from land-use change in 1970 (Houghton, 1999; Houghton *et al.*, 1983). Indeed, land clearing for all forms of agriculture has made a huge contribution to global climate change through release of CO_2 from biomass and soils. This process continues, and currently annual net release of C from agricultural activities, particularly tropical deforestation, is estimated to be about 1.7 Pg/year or about 25% of fossil fuel emissions (Malhi *et al.*, 2002). Loss of soil carbon is an important contributor to this source, highlighting the important role that soils play within the terrestrial carbon cycle. Since major agricultural expansion began in about 1860, losses in soil carbon stocks due to land-use change are estimated to be between 22 and 39 Pg of carbon, representing 25 to 29% of all carbon released due to land-use change (Lal *et al.*, 1997). Recent evidence also indicates a negative feedback with respect to soil carbon loss and climate change, in that climate change has been linked with unexpected carbon losses observed in soils across England and Wales under all land-use types (Bellamy *et al.*, 2005). Land degradation was previously considered a biodiversity conservation issue as habitat was lost, and a local food production problem as soils become less productive as a consequence of reduced biomass and soil carbon. It is now also understood to have global ecosystem-level dimensions and ramifications.

Many factors play into the complex problem of the impact of greenhouse gas emissions on the concentration of gases in the atmosphere,

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such as buffering by the world's oceans. While one obvious solution to these problems is to reduce emissions, another is to re-fix the atmospheric CO_2 in ecosystems through photosynthesis. Partial solutions can therefore be found in reversing land degradation and increasing the sequestration of carbon into terrestrial ecosystems (Brown *et al.*, 2002). Forests are important in this regard because they store large quantities of carbon in vegetation and soils. Forests can be both sources of atmospheric CO_2, when disturbed by natural or human causes, and sinks, when vegetation and soil carbon accumulate after disturbance. When this carbon fixation is semi-permanent, such as in undisturbed forests or recalcitrant soil organic matter, it is called 'carbon sequestration'. Recently, this strategy for mitigating atmospheric CO_2 increases has been incorporated into international conventions related to climate change. Specifically afforestation and reforestation projects have been included in the Kyoto Protocol Clean Development Mechanism Framework.

Water supply and carbon sequestration

Water supply and scarcity has also received increasing attention over the last decade, primarily driven by alarming figures (WHO, 2006) reporting that 1.2 billion people lack access to safe and affordable water for their domestic use. Many of these are the rural poor, who lack water not only for domestic purposes but also to sustain agricultural livelihoods (Rijsberman *et al.*, 2005). Numerous projections with regard to water supply and scarcity focus on the growing global population and their needs for domestic and agricultural water. It is estimated, for example, that water diversions for agriculture must rise between 12 and 27% by 2025 to meet growing food needs (Shiklomanov, 1998; IWMI, 2000; FAO, 2003). Many estimates agree that up to two-thirds of the world population will be affected by water scarcity over the next few decades (Alcamo *et al.*, 1997, 2000; Raskin *et al.* 1997; Seckler *et al.* 1998; Vorosmarty *et al.* 2000; Wallace 2000).

These discussions, however, have rarely considered the relationship between increased freshwater use and global climate change mitigation. This is partly because water accounting generally has only considered surface runoff and groundwater as the available water supply. This prevailing paradigm in water use and supply accounting has lately been revisited, most notably through ecosystem evapotranspiration studies (L'vovitch and White, 1990; Gordon *et al.*, 2005), the introduction of the concepts of green and blue water management in agriculture (Falkenmark, 1995; Rockström *et al.*, 1999), and in the forestry sector (Calder, 2000). In addition, that carbon fixation through biomass production requires water consumption is an underappreciated fact. Terrestrial carbon fixation (with the exception of the precipitation of calcium carbonate) is the result of plant growth and photosynthesis. This process requires water from the ecosystem, which, if an increase in carbon baselines is achieved, almost certainly means an increase in on-site evapotranspiration or local water use. Water allocations to Clean Development Mechanism (Afforestation and Reforestation) (CDM-AR) may therefore in some cases mean direct diversions of water from other uses, with implications for food security, ecosystem functioning and environmental services. Only recently have a few studies highlighted the implications of global climate change mitigation strategies on water use (cf. Berndes, 2002; Heuvelmans *et al.*, 2005). One analysis of bioenergy production concluded that large-scale expansion of energy crop production would require water consumption equal to that which is currently used for all crop production (Berndes, 2002) and brought the implications of this new demand for water into sharp focus.

In this chapter, we focus on two environmental issues on which the Kyoto Protocol treaty, and CDM-AR projects in particular, may have direct impacts: ongoing human-induced land degradation and the water-use implications of carbon sequestration projects. We briefly present an overview of afforestation/reforestation and terrestrial carbon fixation as a climate change mitigation measure, and evaluate its importance and potential contribution, within the Kyoto Protocol framework. We examine the extent, location, productivity, current land use and population of land suitable for CDM-AR, and evaluate the area of this land that will be required to satisfy carbon emission offset limits. In particular, we address the potential scope for CDM-AR to address land degradation, and, with a simple water balance model, evaluate potential water-use impacts. Results are derived from a global geospatial analysis that estimates the impacts on land and water resources, allowing us to explore these questions at a regional to global level.

Background

International conventions

With the adoption of the Kyoto Protocol in 1997, for the first time an international treaty now provides an opportunity for environmental service payments relevant to the problem of ongoing land degradation. In 1992, the United Nations Framework Convention on Climate Change (UNFCCC) was the first international convention to recognize the problem of climate change. The UNFCCC set the political goal to stabilize atmospheric CO_2 concentrations at a level that avoids dangerous climate change. The risks to food production and the importance of adaptation were particularly highlighted. In 1997, specific, legally binding targets and timetables for cutting emissions were developed and adopted as part of the Kyoto Protocol to the UNFCCC. The Kyoto Protocol allows various mechanisms for developed countries (Annex 1) to achieve these targets: joint implementation projects and Clean Development Mechanism (CDM) projects. Joint implementation projects offer 'emissions reduction units' for financing projects in other developed countries. CDM projects provide credit for financing emissions-reducing or emissions-avoiding projects in developing countries (Non-Annex 1).

The CDM is expected to be an important new avenue through which governments and private corporations can promote sustainable development and the transfer of clean technologies. Owing to the role of forests in regulating carbon cycles, i.e. their ability to be both source and sink of carbon, and that these processes can be controlled by human activities, forest and land-use-change activities were included in the Kyoto Protocol and the CDM (Brown *et al*., 2002). The inclusion of afforestation and reforestation, and the rules governing eligibility of these carbon offsets credits, were and are, however, controversial, generating ample debate during the various rounds of negotiations (cf. Kolshus, 2001; Noble and Scholes, 2001; Torvanger *et al*., 2001; Forner and Jotzo, 2002). Controversial issues include a basic questioning of the actual emissions reduction efficacy of carbon sequestration ('sink' projects) and/or whether this mechanism actually allows developed countries to avoid their obligations by essentially 'buying their way out' too inexpensively. Other issues include the lack of 'permanency' in this approach, i.e. the fact that a forest fire or harvesting will quickly release any sequestered carbon. There is, in addition, an uneasiness expressed concerning the essentially different nature of carbon releases derived from fossil fuel, and whether or not these latter emissions can be realistically offset by carbon sequestered in living biomass as a means to mitigate increasing atmospheric CO_2. These concerns might be somewhat misplaced, however, considering that approximately 25% of the extra atmospheric CO_2 has come from land-use change, and release of carbon from living biomass and soils. In 2001, the Subsidiary Body for Scientific and Technological Advice (SBSTA) commissioned a report to explore a series of issues associated with sink projects, including how carbon sequestration should be measured and verified, leakage, land conflict, and environmental considerations, as well as various technical and scientific aspects of carbon sequestration in agriculture and forestry. Although the Kyoto Protocol has only just recently entered into force, and the first commitment period is from 2008 to 2012, much effort has already gone into developing CDM projects, with recent achievements surpassing the milestone of 1 billion t of CO_2 equivalents in projected emission reductions. Funds have been set up to support CDM projects around the world, such as the World Bank Prototype Carbon Fund (PCF), and the BioCarbon Fund, targeted specifically towards carbon sequestration projects. In addition, there have been various capacity-building activities for recipient countries, and significant private sector activity has developed (Huq, 2002).

The clean development mechanism

One of the main purposes of the CDM is to assist developing countries to achieve sustainable development, with the multiple goals of poverty reduction, environmental benefits and cost-effective emissions reductions. The CDM is intended to provide a market vehicle through which countries with high rates of CO_2 emissions (developed countries) can offset their emissions by purchasing carbon credits in developing countries, where it is assumed the costs of the carbon offsets will be lower than in the emitting country. Bioenergy production is one CDM strategy, in which biomass is grown (and CO_2 is fixed) and then used for energy production (and CO_2 released), and thus substituting CO_2-neutral energy for fossil fuel energy. CDM sink projects, unlike bioenergy or clean technology transfer projects, require that carbon be sequestered into semi-permanent 'sinks', primarily by growing trees, thus through afforestation and reforestation (CDM-AR) projects. Certain types of activities, such as new tree planting, are currently eligible for CDM-AR consideration, while others, such as conservation of existing forest, are specifically not allowed (Table 6.1). There is considerable optimism in developing countries and the development community that the potential investments in CDM-AR sink projects can be a boon for rural development and environmental protection if properly directed and monitored. Many countries, and many NGOs, are already heavily involved in planning or implementing pilot projects, with numerous research programmes underway to understand how best to implement viable projects with the desired results.

The market for CDM-AR projects is estimated to be up to 1.5 billion dollars, and is limited by the cap on sink credits agreed upon in Marrakech (UNFCCC, 2002). The cap is estimated to allow between 32.6 mt (Kolshus, 2001) and 37.4 mt (Mollicone et al., 2003) of carbon to be traded through CDM-AR projects, representing between 119.6 and 137.0 mt CO_2 equivalents. Based on this range of carbon equivalents and the current range of Certified Emission Reductions (CER) values of US$3 to 15/mt CO_2 equivalent, this represents between 100 and 500 million dollars of investment per year for development projects that sequester carbon in biomass and soils over the first commitment period of 5 years. This is significantly lower than initial projections, owing to lowered estimates for CER prices. Recent CER price estimates reflect relatively low demand, partly resulting from the non-participation by the United States (Forner and Jotzo, 2002), and the exclusion of these credits from the EU Emissions Trading Scheme. Nevertheless, this still represents significant investment in sustainable development. On the project level, the actual amount of income from the carbon credits is likely to be very small compared with revenue returns generated by wood harvest (if this is planned). Thus, the income from carbon credits is more likely to be an incentive allowing investors, and particularly small farmers, to overcome barriers to entry related to the length of initial return to investment. This incentive will be available to land-use decision makers, and, at least in some cases, may be sufficient to make choices which include afforestation over other competing land uses, such as agriculture.

For CDM-AR projects, the devil is in the detail

Carbon fixation projects continue to be controversial, and developing the rules governing their inclusion into global climate change treaties

Table 6.1. CDM-AR eligible and ineligible activities.

CDM-AR eligible	CDM-AR ineligible
New, large-scale industrial plantations	Forest conservation
Introduction of trees into existing agricultural systems (agroforestry)	Improved forest management
Small-scale plantations by landowners	Reduced-impact logging
Establishment of woodlots on communal lands	Enrichment planting
Rehabilitation of degraded areas through tree planting or assisted natural regeneration	Avoided deforestation
Reforestation of marginal areas with native species (e.g. riverine areas, steep slopes, around and between existing forest fragments through planting and natural regeneration)	
Establishment of biomass plantations for energy production and the substitution of fossil fuels	

has been long and arduous. Reforestation and/or afforestation is land-use change, requiring the cessation of current land-use activities with a shift to forestry. This implies a fundamental but complex change in livelihood strategies, and biophysical and biogeochemical processes on site. This gives rise to several unique challenges in both carbon accounting and project implementation:

- Perverse incentives: there is significant concern that the CDM could set up perverse incentives which could exacerbate ongoing deforestation or reward countries for recent deforestation. Thus, only lands that were deforested before 1989 are currently eligible. This definition has been challenged for use in CDM activities because official records in Non-Annex I Parties are imperfect and may not be available for that date (31 December 1989).
- Defining ‘forest’: this is a difficulty because of the large number of definitions of forest currently in use (Lund, 2002). The choice of a threshold value to be used in the definition of forest (ranging from 10 to 30% of tree canopy cover) has significant implications for the amount of land available within countries for CDM-AR (Verchot *et al.*, 2006).
- Setting carbon baselines: to ensure that the C fixation which is credited as sequestered is additional to the C sequestration that is already likely to have occurred on a parcel of land under existing land-use practices, it is necessary to establish a baseline for the C accounting.
- Leakage: the unanticipated loss of net greenhouse gas reductions as a result of project activities is referred to as ‘leakage’. If the conversion of a parcel of land to forest causes deforestation in an adjacent area, this will have a significant negative impact on a carbon sink’s effectiveness.
- Non-permanence: since carbon is stored in the above-ground biomass, there is a continuous risk of re-emission of carbon stored in forest sinks through fire, pests and human activity. This makes the CDM-AR sink project essentially temporary in nature.
- Environmental issues: reforestation and/or afforestation can have unintended consequences and contribute to ecosystem degradation. Loss of biodiversity or other ecosystem services can result from establishment of extensive, fast-growing plantation forests. Additionally, some forestry activities may increase erosion, such as planting and establishment, and access roads, which can cause major disturbances (Bosch and Hewlett, 1982). The water balance in downstream communities may be negatively affected as a consequence. On-site hydrological effects of afforestation are mainly positive, including reduced runoff and erosion, improved microclimate and increased control over nutrient fluxes. The off-site effects may be mainly negative, such as lower baseflow, but in many cases the off-site effects of increased water use may be beneficial for downstream users.
- Social issues: projects can potentially affect the local society and economy, with, for instance, the local population losing access to land. This can be especially relevant to local land-tenure issues such as indigenous land claims, if treaties and agreements are signed at the national level without regard for local concerns or the equitable sharing of benefits. Changes in local economic activity can also affect key factors in sustainable development, such as gender workloads (for example, increasing women’s workload by requiring them to go farther for firewood and water). This implies that effective carbon sink projects must be integrated into local sustainable development, and involve far more than simply planting trees (Smith and Scherr, 2002).

To make CDM-AR a positive development vehicle, rules have been agreed upon that attempt to reduce the risk of ‘perverse incentives’ that may result in social or environmental harm, and that adequately verify carbon sequestration, and local environmental and sustainable development benefits. Methodologies are being developed for baseline determination and for monitoring carbon stocks. The following analysis aims to contribute to this understanding to ensure that resultant types of global treaties are designed and implemented in a way that results in the greatest possible benefit.

Analysis and Discussion

CDM-AR suitable land and its characteristics

A global analysis identified the location of suitable land at the global, regional and national scales, and further investigated the ancillary characteristics of these areas in terms of their socio-ecological characteristics, productivity levels, hydrological impact and land degradation status. It was based on global-scale land-suitability modelling that used a spatially explicit approach, and higher global data resolution than previous studies (30 arc-seconds), to estimate the land area that is biophysically suitable for CDM-AR projects while meeting UNFCCC eligibility guidelines. The details of this geospatial global modelling approach are described in Zomer *et al.* (2006). Briefly, a diverse set of global environmental geospatial datasets (Table 6.2) was used to derive the set of parameters required to model and map suitable lands. A spatial modelling procedure was developed and implemented in ArcGIS (ESRI, Inc.) using AML programming. The land-suitability analysis was mapped and tabulated globally, regionally and nationally, for all eligible countries. Results of the national analyses are interactively available online for each country using the ENCOFOR CDM-AR Online Analysis Tool, available at http://csi.cgiar.org/encofor/.

The global analysis (Zomer *et al.*, 2006) identified all land surface areas that meet a minimal set of eligibility criteria (Table 6.3), in both biophysical and regulatory terms, as suitable for CDM-AR (Fig. 6.1). Global totals are reported as the sum of five regions (Table 6.4), which cover most of the developing countries with significant CDM-AR potential. Approximately 725 Mha of land was initially identified as biophysically suitable. Large tracts of suitable

Table 6.2. Environmental and other global geospatial datasets used to derive parameters for the global analysis of CDM-AR Land Suitability (Zomer *et al.*, 2006). Spatial resolution: 0.5–1.0 km (15–30 arc-seconds).

Database	Source
VMAP 1 – Country Boundaries National Imagery and Mapping Agency	NIMA, 1997
Global Ecosystem Land Cover Characterization Database v. 2.0	USGS, 1993
MODIS Vegetation Continuous Field – Tree Cover	Hansen *et al.*, 2003
Topography – SRTM DEM	USGS, 2004
World Database of Protected Areas	IUCN/UNEP – WDPA Consortium, 2004
WorldClim	Hijmans *et al.*, 2004
Maximum Available Soil Water	Digital Soil Map of the World – FAO, 1995
Climate Station Dataset	FAOCLIM – FAO, 2001
Gridded Population of the World 2000	GPW3 – CIESIN and CIAT, 2005
Global Map of Ecosystem Rooting Depth	ISLSCP – Schenk and Jackson, 2002
MOD17A3 – MODIS Net Annual Primary Production	Running *et al.*, 2000

Table 6.3. Eligibility criteria for lands excluded a priori from land-suitability analysis.

Factors	Exclusion criteria
Arid and semi-arid lands	Aridity index < 0.65 (mean annual precipitation/mean annual evapotranspiration)
Elevation	Above 3500 m and/or timberline
Cover type	Water bodies Urban Tundra Intensive agriculture Forest cover > 30%

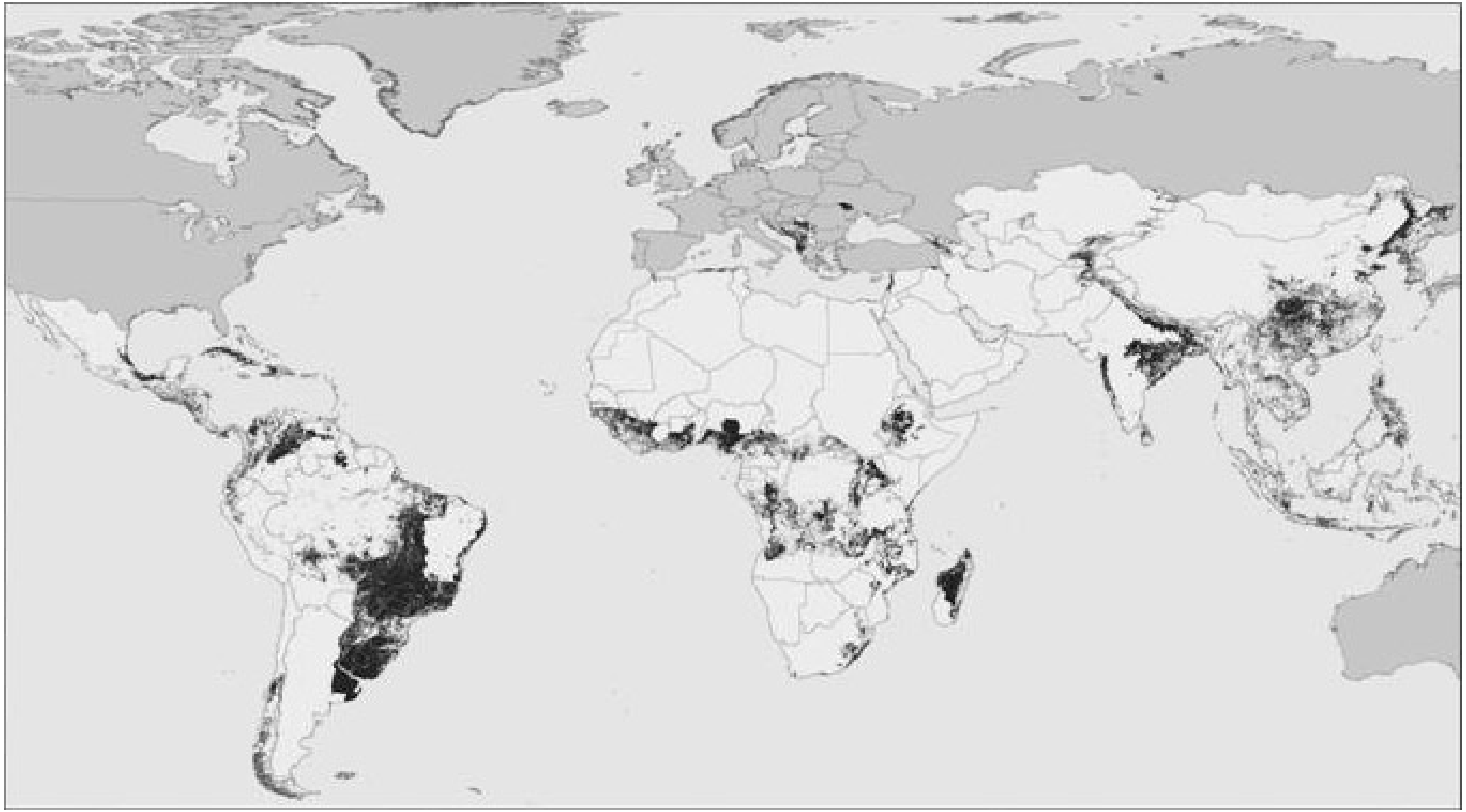


Fig. 6.1. Global map of CDM-AR suitable land within Non-Annex 1 countries, as delineated by the land suitability analysis (Zomer *et al.*, 2006). A 30% crown cover density threshold was used to define forest, with protected areas not included.

Table 6.4. CDM-AR suitable land by existing land-use type, by total area (Mha) and percentage of the total suitable land, regionally and globally.

	Existing land-use type								
	Cropland		Mixed shrubland/ grassland		Savannah		Barren/ sparsely vegetated		Total
Region	Mha	%	Mha	%	Mha	%	Mha	%	Mha
East Asia	59	63	20	21	14	15	0	0.1	93
Sub-Saharan Africa	54	28	8	4	132	68	1	0.4	195
South America	172	52	29	9	132	40	1	0.2	333
South Asia	48	76	3	5	12	18	0	0.1	63
South-east Asia	31	76	3	8	6	16	0	0.2	41
Global	364	50	63	9	296	41	2	0.2	725

land are found in South America (46% of all suitable areas globally) and sub-Saharan Africa (27%), reflecting the greater land mass of these regions and, to a certain extent, lower population densities. Much smaller amounts of land are available in Asia, the three Asian regions together offering about 200 Mha, compared with more that 330 Mha in South America and almost 200 Mha in Africa. Within respective regions, the range of available land extended from only 8% of the total land surface area in South-east Asia, to more than 19% of South America.

These figures compare well with earlier studies that have explored aspects of the question of land availability, first by asking how much land is available for reforestation (Nilsson and Schopfhauser, 1995; Trexler and Haugen, 1995; Winjum *et al.*, 1998) and what the potential is for carbon sequestration (Noble and Scholes, 2001; Yamagata and Alexandrov, 2001; see Jung, 2005 for an extensive listing by country). The area available for tree plantations was variably estimated at 345 Mha (Nilsson and Schopfhauser, 1995), 465 Mha (Sedjo and Solomon, 1989), and 510 Mha (Nordhaus, 1991). Nilsson and Schopfhauser's (1995) and Trexler and Haugen's (1995) studies together suggest that 700 Mha of land could be available for carbon sequestration and conservation globally, including 138 Mha for slowed tropical deforestation, 217 Mha for regeneration of tropical forests, and 345 Mha for plantations and agroforestry.

Land use

A few land-use types constitute the majority of suitable lands: primarily agricultural land use, savannah and, to a lesser extent, shrub and grasslands (Fig. 6.2a). Across the five regions, more than 50% of all the eligible area is classified as within non-intensive or subsistence, agricultural land-use type, constituting more than 364 Mha (Table 6.4). This is not surprising, and in line with many of the assumptions in the literature about available land (Smith and Scherr, 2002). Since the criteria specify that forested areas are not eligible, and since much deforestation has occurred to make room for agriculture, by elimination, agricultural lands are the most likely to be available. Most agricultural areas, even after intensive production sites have been excluded from the analysis, are ideal for tree growth, with deeper soils, better climate and adequate moisture, and also meet the CDM-AR criteria, i.e. are not currently forested.

Much attention has been given to the potential of small farmers and communities to participate in CDM-AR through agroforestry-type practices. This may constitute an option for significantly increasing the carbon sequestration within rural and agricultural landscapes. This is shown to be increasingly important, since currently in all regions except Africa, a majority of the identified suitable land is under agricultural land use, and this can be expected to increase with current land conversion rates. This is particularly relevant to

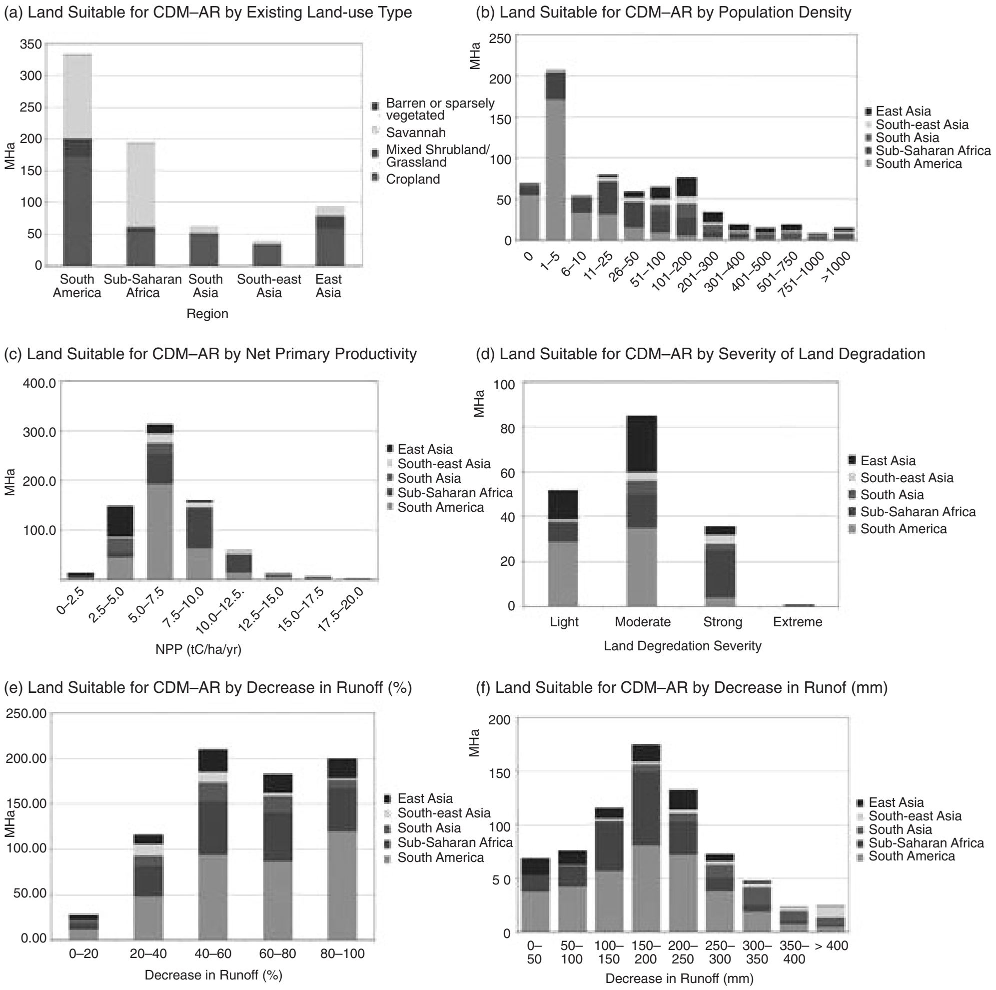
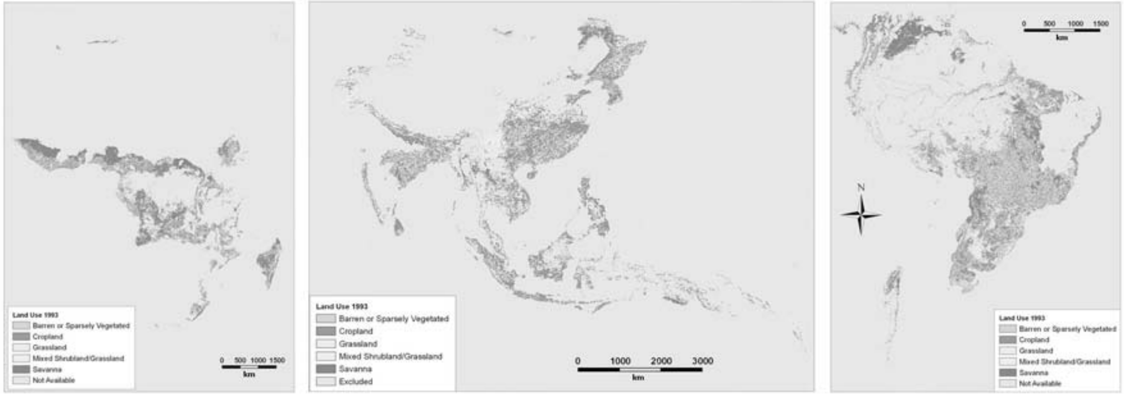


Fig. 6.2. Area distribution of socio-ecological characteristics within CDM-AR suitable areas: (a) existing land use; (b) population density (people/km^2); (c) net primary productivity (NPP) (tC/ha/yr.); (d) degree of land degradation; (e) decrease in runoff (%) with land-use change to CDM-AR; (f.) decrease in runoff (mm) with land-use change to CDM-AR.

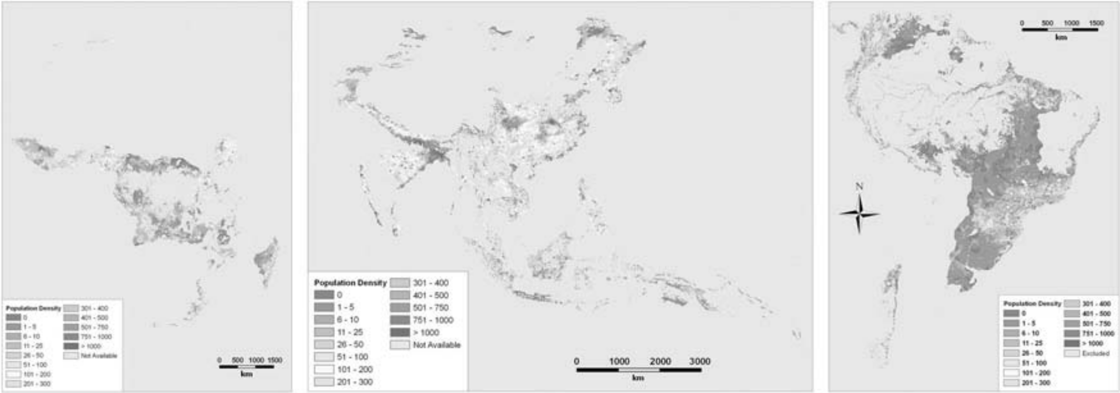
the evaluation of food security concerns associated with large-scale conversion to tree plantations. Both South Asia and South-east Asia have a very high percentage of the suitable land (76%) under agricultural land-use types, with much smaller areas of shrubland and savannah, reflecting the high population densities and pervasive agricultural production found in these regions. It is interesting to note that much of the hilly land in South Asia and the Himalayan foothill areas has canopy cover percentages above the threshold for forest, and is therefore not eligible, although many of these areas are under various forms of intensive agricultural production.

About 50% of all globally available land for CDM-AR is shrubland and savannah. Suitable areas in sub-Saharan Africa and South America (Fig. 6.3a) included large tracts of savannah (132 Mha, 68% of suitable savannah) and mixed shrubland/grassland (29 Mha, 52% of suitable shrubland/grassland), respectively, where it is likely that substantial pastoralist, other forms of livestock production activities

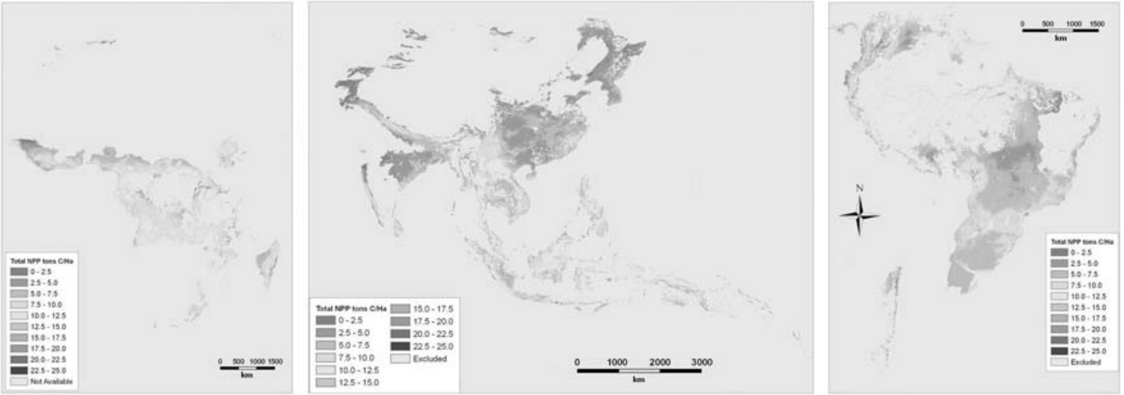
(a) Land Use



(b) Population Density



(c) NPP



(d) Land Degradation

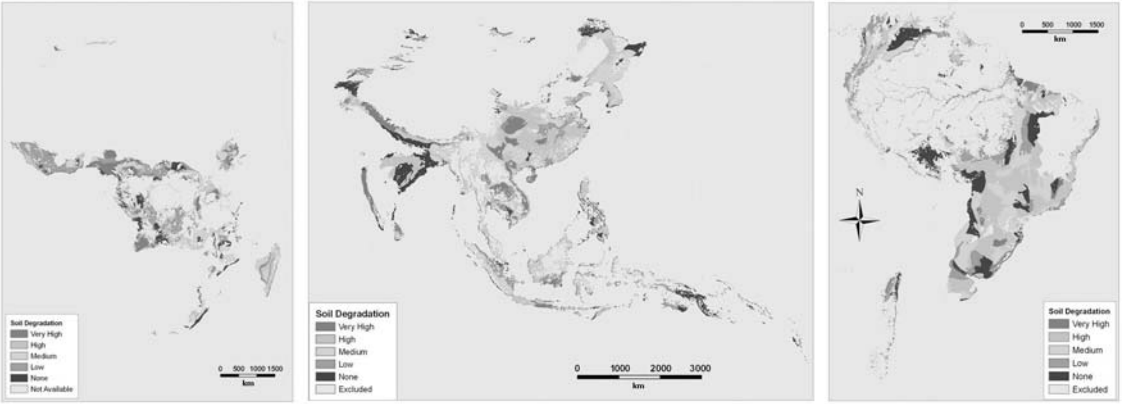


Fig. 6.3. Socio-ecological characteristics maps of CDM-AR suitable areas for South America (left), South and east Asia (centre) and Africa (right): (a) existing land use; (b) population density (people/km^2); (c) net primary productivity (NPP) (tC/ha/yr.); (d) severity of land degradation. Severity of land degradation is a specific variable, designed by GLASOD authors to map the overall seriousness of soil degradation by taking into account both the degree and extent of soil degradation to provide a unique variable. Land degradation severity should not be confused with soil degradation degree, which was used for the area calculation of soil degradation.

and other subsistence livelihoods are evident, even in less populated areas. Since the criteria used in the model generally exclude areas prone to water stress (aridity index > 0.65), the included savannah areas can be considered as fairly productive. In sub-Saharan Africa, however, it is likely that much of this savannah, although identified as biophysically suitable for tree growth, has a very low probability of being converted to CDM-AR. Even so, these savannahs do have agroforestry potential, along with other restoration activities with significant carbon sequestration benefits, and could play a more pronounced role in global carbon-fixation strategies. Restoration of dry forest types, for example, in the highlands of Ethiopia (Aerts *et al.*, 2004), the dry zones of Madagascar, or on the pastures of Central America, could have significant carbon sequestration potential over the long term, despite slow growth.

Population

Patterns of rural population density on these lands vary widely between regions (Fig. 6.3b). Population density is here considered a measure of utilization, and it is assumed that at high densities, less land is likely to be converted to tree plantations. In addition, it is assumed that in areas of high rural population densities, competition for food production, and food security issues, will inhibit the adoption of CDM-AR projects. Globally, more than 50% of all identified areas have population densities of fewer than 25 people/km^2, i.e. have relatively low densities; more than 35% have densities of fewer than 5 people/km^2. In east and South Asia, however, population densities may represent a real limitation on suitable land (Table 6.5). In India for example, 83% of all suitable areas have a population density greater than 100 people/km^2, with 54% having greater than 200/km^2 and almost 23% with a population density greater than 500 people/km^2. Otherwise, population densities on suitable lands are relatively low. For example, suitable areas in South America have the lowest population levels, with 95% of all identified areas having population densities of fewer than 100 people/km^2, and almost 70% with a population of fewer than five people. Sub-Saharan Africa (Fig. 6.2b) has less empty lands, but still has relatively low population densities associated with these identified areas. Much of the low population density classes in South America and sub-Saharan Africa comprise savannah, although, particularly in South America, substantial areas of very low population density are classified as agricultural land-use types. In South-east Asia, degraded forest areas account for much of the low-population density areas.

Productivity of suitable areas

Results from the analysis (Zomer *et al.*, 2006) of the NASA MODIS MOD-17A3 NPP product (Running *et al.*, 2000) show that land suitable for CDM-AR generally falls into moderately low to moderate productivity categories (Fig. 6.2c), indicating that higher productivity lands, mainly intensive and irrigated cropping and forested areas, were eliminated by the CDM-AR guidelines, thus leaving proportionally large amounts of less productive land and borderline marginal areas for afforestation/reforestation. Likewise, many of the most marginal areas were also eliminated due to aridity, thus giving a generally normal distribution of productivity classes, centred on a moderately productive mean. Globally, 88% of all available land had an actual NPP below 10 t C/ha/year (Table 6.6). About 75% of available land in Africa and South-east Asia (Fig. 6.3c), and almost all available land in South America (92%), South Asia (96%) and east Asia (98%), indicated an actual NPP less than 10 t C/ha/yr. These results indicate productivity levels consistent with global values (Esser *et al.*, 2000; Scurlock and Olson 2002), and reflect the abundant inclusion of marginal and subsistence cropping areas and lower-productivity grassland.

Land area required to meet the CDM-AR cap

The Marrakech accords negotiated a framework for the first commitment period of the Kyoto Protocol (2008 to 2012), where developed countries may claim credit for carbon sequestration in developing countries. In response to widespread concerns that CDM sink projects would negatively affect CO_2 emission reduction aims (e.g. Greenpeace 2003), a cap on CDM-AR emission

Table 6.5. CDM-AR suitable land by population density class given by area (Mha) (percentage of the total CDM-AR suitable land regionally and globally in parentheses).

	Population density class (people/km^2)									
	≤ 10	11–25	26–50	51–100	101–200	201–300	301–400	401–500	> 500	Total
Region	CDMR-AR suitable land area (Mha)									
East Asia	4 (4)	4 (4)	7 (8)	14 (15)	23 (25)	13 (14)	8 (8)	6 (7)	14 (15)	93
Sub-Saharan Africa	63 (32)	40 (21)	30 (15)	26 (13)	21 (11)	5 (3)	3 (2)	2 (1)	4 (2)	195
South America	260 (78)	31 (9)	15 (5)	10 (3)	5 (2)	4 (1)	2 (1)	2 (0)	4 (1)	333
South Asia	1 (2)	0 (1)	2 (3)	7 (12)	18 (29)	10 (15)	5 (7)	4 (7)	16 (25)	63
South-east Asia	5 (11)	4 (10)	5 (13)	7 (18)	9 (21)	3 (8)	2 (4)	1 (33)	5 (11)	41
Global	332 (46)	80 (11)	59 (8)	65 (9)	76 (11)	35 (5)	20 (3)	16 (2)	43 (6)	725

Table 6.6. CDM-AR suitable land by NPP productivity class given by area (Mha) (percentage of the total suitable land regionally and globally in parentheses).

	NPP productivity class (t C/ha/yr)							
	0–2.5	2.5–5.0	5.0–7.5	7.5–10.0	10.0–12.5	12.5–15.0	> 15.0	Total
Region	CDMR-AR suitable land area (Mha)							
East Asia	6.1 (7)	62.2 (67)	19.3 (21)	4.3 (5)	1.0 (1)	0.4 (0)	0.0 (0)	93
Sub-Saharan Africa	1.5 (7)	9.2 (5)	58.9 (30)	78.9 (41)	36.7 (19)	4.0 (2)	5.3 (3)	195
South America	2.7 (1)	45.5 (14)	193.9 (58)	63.9 (19)	14.7 (4)	7.2 (2)	5.3 (2)	333
South Asia	3.9 (6)	29.7 (47)	23.3 (337)	4.1 (7)	1.3 (2)	0.6 (1)	0.3 (1)	63
South-east Asia	0.2 (0)	2.7 (7)	18.1 (44)	9.5 (23)	5.6 (14)	3.6 (9)	1.2 (3)	41
Global	14 (2)	149 (21)	314 (43)	161 (22)	59 (8)	16 (2)	12 (2)	725

reduction offsets was set at 1% (per annum) of the total global emission reduction target. In order to estimate the amount of land required to fully meet this cap on emission credits (CERs), a conservative range of carbon sequestration rates (4 to 8 t C/ha/year) was used. This estimate was based on a literature survey of tropical tree plantation growth rates and IPCC (2000) estimates, and assumptions including accounting for baseline and the lower productivity of marginal or degraded areas. It is assumed that many of these projects, which are likely to have goals beyond maximizing profitability, are likely to be less productive than typical intensively managed commercial tree plantations as they are found in the tropics. This conservative estimate indicates that from 4 to 8 Mha of land planted with fast-growing tree species will easily satisfy the total allowable supply of CERs. This is a small figure globally, representing less that 2% of the area we have identified as suitable.

Potential of CDM-AR to improve degraded lands

To explore the potential of the CDM mechanisms to contribute meaningfully to sustainable development and more specifically to the large-scale problem of ongoing land degradation, the CDM-AR land-suitability analysis (Zomer *et al.*, 2006) was overlaid on the Global Assessment of Human-Induced Soil Degradation, (GLASOD) spatial dataset. GLASOD is based primarily on expert judgment (Oldeman, 1991), and is currently the only available global assessment of soil degradation. It is at a very coarse resolution (1:10M), makes broad generalizations spatially and tends to highlight very apparent degradation, such as erosion or desertification, but may not have captured other degradation processes such as nutrient depletion or acidification. The authors plainly state the drawbacks of this study, and warn that the resulting global database is not appropriate for national breakdowns. Many global interpretations are, however, based on GLASOD or derived products, as no other database is currently available at the global scale. Given that proviso, to analyse the area affected by soil degradation for CDM-AR suitable areas, the GLASOD was translated from polygon coverages to raster grids, which were then masked using the CDM-AR suitability grids to calculate areas for each degradation type and degree, and aggregated for the four different degradation degrees at global and subcontinent scale. As per GLASOD instructions (Oldeman *et al.*, 1991), the units of degradation *severity* (low, medium, high and very high) are used for mapping purposes (Fig. 6.3d), where the units represent both the degree of degradation and the extent of that degradation within the mapping unit. Area estimations (Fig. 6.2d and Table 6.7) are made of degradation *degree* (light, moderate, strong and extreme), by initially calculating the area for each combination of degradation type and degradation degree, and summing over the area of interest. This defined the general overview of the overlap of land with potential for CDM-AR within areas delineated as in the various GLASOD soil degradation severity classes.

Table 6.7. CDM-AR suitable land by GLASOD (Oldeman *et al.*, 1991) land degradation severity class, given by area (Mha) (percentages of total CDM-AR suitable land regionally and globally in parentheses).

	Soil degradation severity					
	None	Light	Moderate	Strong	Extreme	Regional total (Mha)
Region	Total CDM-AR suitable land area (Mha)					
East Asia	51 (55)	13 (14)	25 (26)	4 (4)	0	93
Sub-Saharan Africa	150 (77)	8 (4)	15 (8)	21 (11)	1	195
South America	266 (80)	29 (9)	35 (10)	4 (1)	0	334
South Asia	52 (83)	1 (1)	6 (10)	3 (5)	0	62
South-east Asia	32 (77)	1 (4)	4 (11)	4 (9)	0	41
Global	551 (76)	52 (7)	85 (12)	36 (5)	1	725

Globally, GLASOD estimates that human-induced degradation of soil has occurred on 15% of the world's total land area (13% light and moderate, 2% severe and very severe), mainly resulting from erosion, nutrient decline, salinization and physical compaction. Based on GLASOD, Wood *et al.* (2000) estimate that 40% of agricultural land in the world is moderately degraded and a further 9% strongly degraded. Overlay of the GLASOD assessment with the Zomer *et al.* (2006) analysis classifies approximately 25% of the identified CDM-AR potential areas as affected by some degree of degradation (Fig. 6.2d and Table 6.7). More than 20% of all the land identified in east Asia, South Asia and South-east Asia combined falls into the moderate and strong degradation severity categories (Fig. 6.2d). Moderately degraded lands have greatly reduced productivity, requiring major improvements that are often beyond the ability of local farmers in developing countries. Severely degraded lands are those considered essentially beyond remediation without major engineering work (Oldeman *et al.*, 1991). In east Asia, 45% of the suitable lands may have some degree of degradation. In Africa particularly, but South America as well, much of the land in degraded categories is savannah and grasslands, reflecting the role of livestock and grazing in land degradation processes.

The large amount of land identified as suitable for CDM-AR within GLASOD degraded land classes is troubling. It is likely that afforestation, agroforestry and conservation techniques using trees could contribute significantly towards improving the quality of these lands. The question remains, however, whether CDM-AR provides the needed targeting or level of international assistance to reclaim degraded land. In fact, CDM-AR projects designed to rehabilitate degraded lands are at a disadvantage financially due to slower growth on poorer soils and marginal sites. Many tree plantations worldwide are found on relatively fertile land, where higher growth rates can provide higher rates of returns for investors. More likely scenarios are approaches that seek to improve and mitigate ongoing light degradation, although these lands are also considered to have reduced productivity. They therefore also suffer from the disadvantage of finding it harder to provide returns to investors, if incentives are not adequate.

Agroforestry initiatives that offer significant opportunities for projects to provide benefits to smallholder farmers can also help address land degradation through community-based efforts in more marginal areas. Since intensively cultivated agricultural land and all irrigated systems were excluded from our analysis, much of the land identified as suitable is likely to be these more marginal areas and/or smallholder and subsistence farming systems, as represented in the mixed rainfed farming category, and exhibit ongoing degradation. The potential of CDM-AR projects to contribute to development through community-based, or small-farmer-oriented, approaches has been enthusiastically embraced by many aid and development organizations, as well as national governments. As an example, the World Bank-sponsored BioCarbon Fund specifically seeks to promote community-based CDM-AR. In Mexico and Uganda, community-based efforts are attempting to design CDM-AR that includes hundreds to thousands of small farmers adopting agroforestry, and increasing carbon stock within the larger mixed farming landscape (http://www.planvivo.org). Likewise, ongoing GEF-funded work in western Kenya attempts to quantify the potential carbon sequestration benefits of improved farming and increased soil organic matter on smallholder farms, in addition to the inclusion of trees in the farming system and the landscape.

Another opportunity to address land degradation that is not possible under existing CDM-AR rules includes rehabilitation of significant quantities of degraded forestland (230 Mha) identified as having been deforested since 1992 (Zomer *et al.*, 2006). These lands are currently excluded as ineligible. Changes in CDM-AR rules to reflect the opportunities for forest landscape restoration, and to substantively address and reverse negative land-use trends, should be considered, and are currently being put forward and debated by various parties. Likewise, it is postulated that prevention is better than rehabilitation, so the most significant impact for CDM to address land degradation might be to encourage ecosystem (i.e. forest) preservation during the second commitment period. This approach, of providing credit for not cutting existing forests and/or improving degraded forest, has significant potential to impact positively ongoing land degradation trends. It does not, however, necessarily offset or curtail emissions, and needs to be tailored to provide mitigation benefits, if it is to be approved. The opportunities for global forest landscape restoration are significant and can have a large impact not only on land degradation, sedimentation and water cycles but can also provide many benefits for biodiversity conservation. The potential of these benefits is not currently included in CDM-AR, and it is very much dependent on the details and the final shape of political negotiations whether this will be allowed in the second commitment period, starting in 2012. Expanding the CDM-AR provisions to contribute to a slowing of deforestation rates, and to actively encourage forest landscape restoration, offers opportunities for addressing both land degradation and biodiversity simultaneously in a holistic approach to conservation and climate change mitigation.

Water-use impacts of CDM-AR

The land-suitability analysis provided the basis for an investigation of the potential hydrologic impacts of widespread adoption of CDM-AR. Zomer *et al.* (2006) used a simple water balance model (Thornthwaite, 1948; Thornthwaite and Mather, 1955) to examine and predict changes in water balance, vapour flows (includes both evapotranspiration and interception losses of water) and runoff resulting from the conversion of existing land-use systems to forestry on the land deemed suitable for CDM-AR. This model (described in detail in Zomer *et al.* 2006) uses spatially distributed climate average values (1950–2000) of monthly precipitation and monthly potential evapotranspiration, land-use classes, land-use-specific vegetation coefficients (crop coefficient, interception coefficient and rooting depth), soil depth and soil water-holding capacity, and returns monthly spatially distributed climate average raster data (1950–2000) representing actual evapotranspiration, surface runoff and soil water content. Results are calculated on a monthly basis for existing land use and proposed CDM-AR scenarios, and the results are aggregated into yearly totals.

Significant variation in increased vapour flow and impact on runoff were evident (Table 6.8) across suitable areas. Both relative impact on water cycles and absolute change in the quantity of water moving away from the site, either as vapour or runoff, were quantified in the analysis. Together they indicate that large areas deemed suitable for CDM-AR would exhibit significant increases in vapour flows (Fig. 6.4) and therefore substantial decreases in runoff (Fig. 6.5), i.e. decrease in water potentially available off-site for other uses. This is particularly evident in drier areas, the semi-arid tropics, and in conversion from grasslands and subsistence agriculture. Fifty per cent of all suitable land had a more than 60% decrease in runoff (Fig. 6.2e). About 27% (200 Mha) is in the highest impact class, exhibiting a 80–100% decrease in runoff. Approximately 60% of the area showed a decrease of less than 200 mm, with slightly more than 13% showing a decrease of more than 300 mm (Fig. 6.2f).

The cap on CDM-AR is currently set at 1% of emission offsets. We thus estimate that just 2–3% of CDM-AR suitable land is eligible for conversion. Hence, direct impacts of CDM-AR on water use at the global and regional scales are unlikely. Local impacts can, however, be very large, and significant changes in CDM rules affecting the amount of land which will eventually be under CDM-AR should take into account these potential impacts in order to optimize the potential benefits of expanded CDM-AR limits. Since there are large amounts of land where water resources will not be negatively affected, or where increased water use would be positive, guidelines can facilitate a spatial optimization of landscapes and land-use change, and promote the establishment of CDM-AR projects within biomes and ecozones where the potential negative hydrologic affects are minimized.

These results are in agreement with the many studies that have shown that runoff from forested and reforested areas is generally lower compared with bare land and grassland (Bosch and Hewlett, 1982; Zhou *et al.*, 2002). As a consequence of afforestation projects using fast-growing conifers, decreased stream-flow levels are commonly observed, both over the entire year (Swank and Douglass, 1974) and during the dry season (Vincent, 1995). Transpiration from trees can potentially be higher than from shorter vegetation because the tree root system may be able to exploit deep soil water (Maidment, 1992) and guarantee higher water availability during

Table 6.8. Decrease in total runoff (mm) and percentage decrease in total runoff with land-use change to CDM-AR suitable land (Mha), regionally and globally.

	Decrease in runoff (mm)								
Region	0–50	50–100	100–150	150–200	200–250	250–300	300–350	350–400	> 400
East Asia	16	14	10	16	18	7	2	0	1
Sub-Saharan Africa	15	19	45	67	30	12	6	3	2
South America	38	42	57	81	72	38	19	8	5
South Asia	0	1	2	8	9	12	17	10	6
South-east Asia	0	1	2	3	3	3	4	4	11
Global	69	76	116	175	132	73	48	24	25

	Decrease in runoff as a percentage of total				
Region	0–20	20–40	40–60	60–80	8–100
East Asia	6	10	25	21	22
Sub-Saharan Africa	0	13	11	3	2
South America	3	12	22	19	9
South Asia	7	33	58	53	48
South-east Asia	11	48	94	87	119
Global	28	116	210	183	200

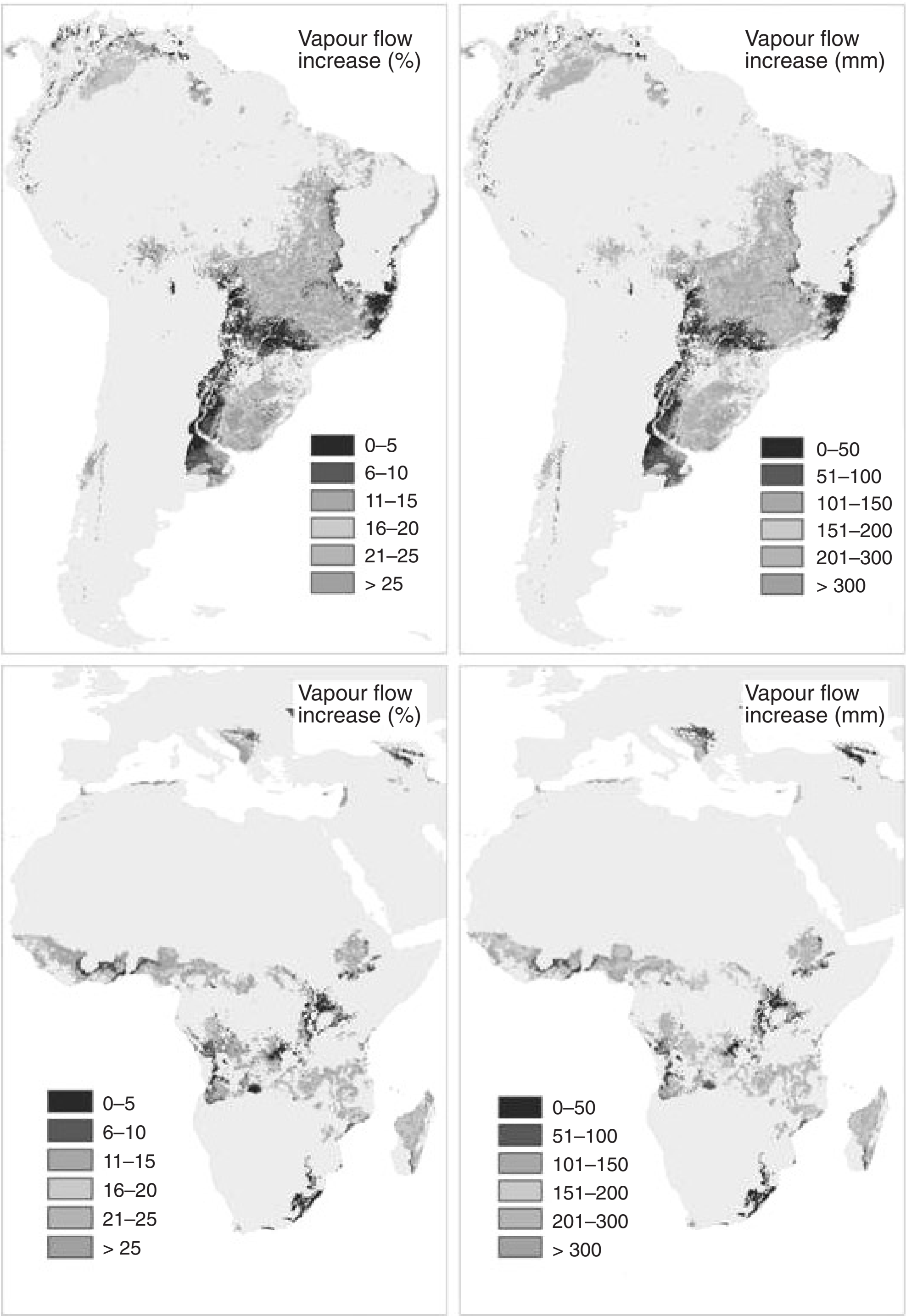


Fig. 6.4. Increases in vapour flow due to changes from existing land use to CDM-AR are shown for South America (above) and Africa (below), in both percentage (left) and absolute values (right).

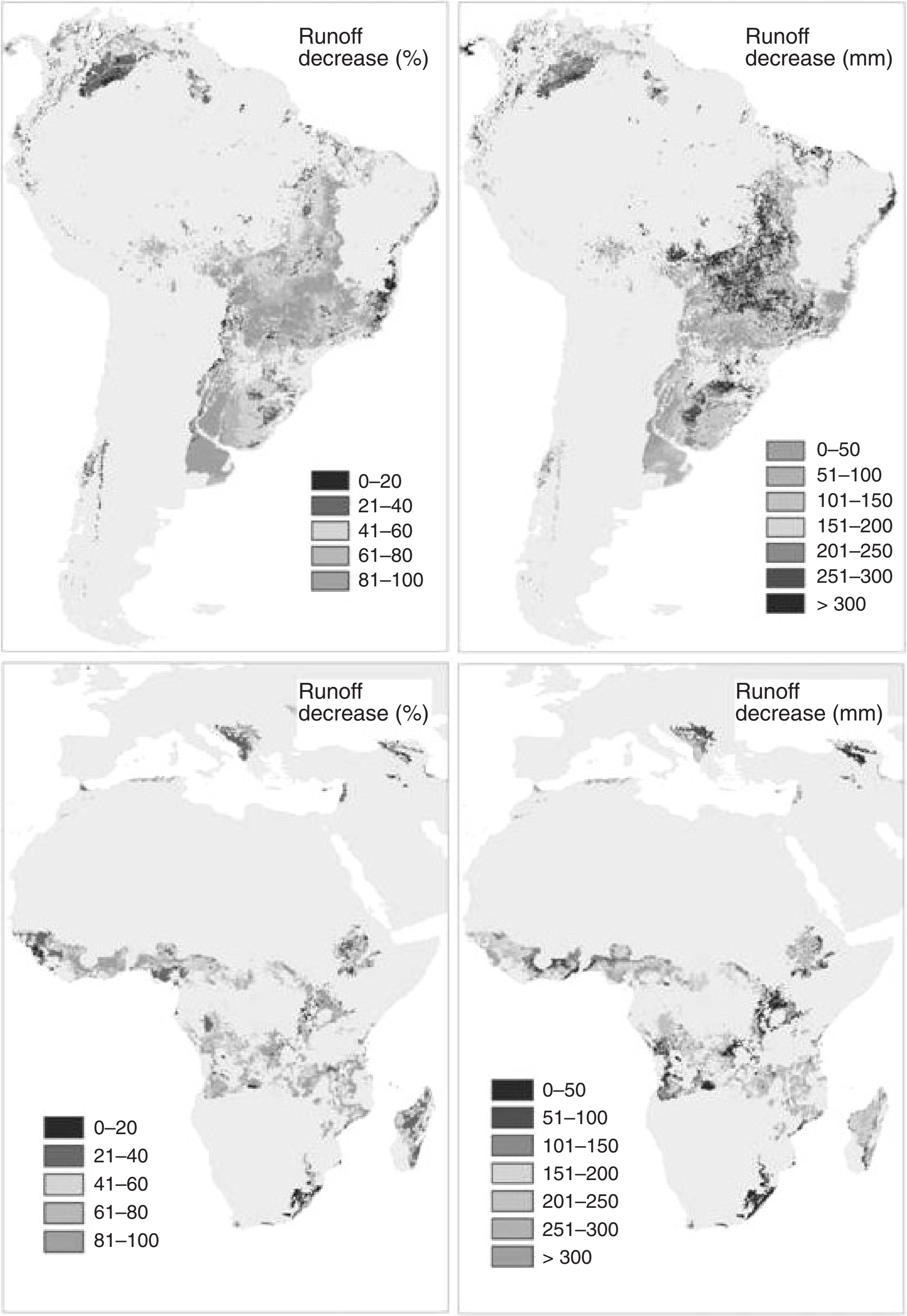


Fig. 6.5. Decreases in runoff due to changes from existing land use to CDM-AR are shown for South America (above) and Africa (below), in both percentage (left) and absolute values (right).

prolonged dry seasons (IPCC, 2000). The ongoing debate on forests and water has lately, however, been the subject of much interest and research (CIFOR and FAO, 2005), and cautions against simple interpretations based on extrapolation of local evapotranspiration to larger-scale hydrologic cycle implications. Ryszkowski and Kędziora (Chapter 11, this volume) and Gedney *et al.* (2006) support the thesis that afforestation is not necessarily a burden for regional and global hydrological cycles.

Conclusion

It is evident that the scale of implementation of the CDM-AR is insufficient to address the severity and scale of ongoing global land degradation processes, given the relatively small amount of land which eventually could come under the CDM-AR in its current configuration. Globally, the supply of land for CDM-AR, and consequently the potential supply of carbon that can be sequestered in terrestrial ecosystems, is far greater than the current cap on CDM-AR credits. It is likely, however, that CDM-AR will play a larger, and increasingly more important, role in climate change mitigation, most probably starting in the second commitment period. Current negotiations also bring the prospect of innovative approaches, which could include avoided deforestation and the restoration of degraded forests, so that credits available from sink projects will increase. More importantly, CDM-AR is the first substantive example of a global and internationally supported ecosystem service payment mechanism, and demonstrates the feasibility of this approach to address significant environmental concerns.

The potential for afforestation and reforestation to address land degradation and provide carbon sequestration benefits in smallholder farming systems is large. Even if, however, the emissions cap is increased for CDM-AR in the second commitment period, allowing more land area to be incorporated into CDM-AR projects, there will still be significant barriers to overcome before it can become a significant land degradation reversing mechanism: high transaction costs when large numbers of smallholder farmers are involved and soil degradation that make projects less competitive. Monitoring and validation costs already significantly affect the viability of smaller or less profitable projects.

Human impacts on the global water cycle, especially in relation to land degradation, are getting increasing attention and are likely to get more in the near future as population continues to rapidly expand. The impact of global redistributions of water use driven by agriculture and land-use change is a major component of ongoing global change (L'vovich and White, 1990), and probably also highly significant climate change processes as well. When taking into account the need for increased food production, and the increased use of water for food, it is unlikely that CDM-AR will significantly affect these resources at the global scale. Locally, however, it is essential that these aspects of food and environmental security be specifically addressed in the project design and implementation stages. In this chapter, we have highlighted that there are potentially significant impacts on the hydrologic cycle resulting from climate change mitigation measures adopted on a global scale. A simple analysis of bioenergy and implications for water use and supply by Berndes (2002) demonstrates that to supply CO_2-neutral energy through bioenergy would require a doubling of water use in agriculture over that currently used on global cropland. The global CDM-AR analysis shows that if the cap on CDM-AR were raised to compensate for a substantially greater offset of carbon emissions through sink projects, there could be significant impacts on local and regional hydrologic cycles. This important dimension of CDM-AR should be formally articulated and taken into account within the CDM-AR rules, especially when addressing issues of sustainability, local communities and food security.

It is important to stress the need to promote positive impacts where CDM-AR is implemented, and highlight the potential to address a variety of land issues in a meaningful way, including land degradation. In particular, the sequestration potential of increasing soil carbon is immense, and this could be promoted through afforestation/reforestation or agroforestry approaches, as well as through improved farming techniques such as conservation tillage, which Lal *et al.* (1997) estimate could sequester 3 Pg C/year on degraded soils. Loss of soil organic matter goes hand in hand with loss of above-ground biomass. The most significant losses in global soil carbon stocks occur when native forest and grassland vegetation is cleared for agricultural production. Many soils (particularly high-organic matter soils in temperate climates, e.g. mollisols in the great plains of the USA) maintain very high levels of productivity for long periods of time, despite these losses. Other soils, especially after years of annual cropping in tropical climates, suffer from degradation processes such as losses in soil carbon, nutrient depletion and reduced water-holding capacity, which can occur quickly and be difficult to reverse (Stocking, 2003). Making provision for both improved soil management in agricultural systems and avoided deforestation in the CDM-AR could extend the provision of ecosystem service payments directly towards addressing the enormous issue of ongoing and increasing land degradation in developing and tropical countries.

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References

Aerts, R., Wagendorp, T., November, E., Behailu, M., Deckers, J. and Muys, B. (2004) Ecosystem thermal buffer capacity as an indicator of the restoration status of protected areas in the northern Ethiopian highlands. *Restoration Ecology* 12 (4), 586–596.

Alcamo, J., Doll, P., Kaspar, F. and Siebert, S. (1997) Global change and global scenarios of water use and availability: an application of WaterGAP 1.0. Center for Environmental Systems Research, University of Kassel, Kassel, Germany.

Alcamo, J., Henrichs, T. and Rosch, T. (2000) World water in 2025: global modeling and scenario analysis. In: Rijsberman, F. (ed.) *World Water Scenarios Analyses*. World Water Council, Marseille, France, pp. 204–242.

Bellamy, P.H., Loveland, P.J., Bradley, R.I., Lark, R.M. and Kirk, G.J.D. (2005) Carbon losses from all soils across England and Wales 1978–2003. *Nature* 437, 245–248.

Berndes, G. (2002) Bioenergy and water – the implications of large-scale bioenergy production for water use and supply. *Global Environmental Change* 12, 253–271.

Bosch, J.M. and Hewlett, J.D. (1982) A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* 55 (1–4), 3–23.

Brown, S., Swingland, I.R., Hanbury-Tenison, R., Prance, G.T. and Myers, N. (2002) Changes in the use and management of forests for abating carbon emissions: issues and challenges under the Kyoto Protocol. In: Swingland, I.R. (ed.) *Capturing Carbon and Conserving Biodiversity*. Earthscan Publications Ltd, London, pp. 42–55.

Calder, I. (2000) Land use impacts on water resources. Land–Water Linkages in Rural Watersheds Electronic Workshop, Background Paper No.l, 18 September – 27 October, FAO, Rome.

CIESIN (Center for International Earth Science Information Network) and CIAT (Columbia University; and Centro Internacional de Agricultura Tropical) (2005) Gridded Population of the World Version 3 (GPWv3). Palisades, NY: Socioeconomic Data and Applications Center (SEDAC), Columbia University, Columbia, New York. http://sedac.ciesin.columbia.edu/gpw.

CIFOR (Center for International Forestry Research) and the FAO (Food and Agriculture Organization) (2005) Forests and floods: drowning in fiction or thriving on facts? *Forest Perspectives* No. 2.

Esser, G., Lieth, H.F.H., Scurlock, J.M.O. and Olson, R.J. (2000) Osnabrück net primary productivity data set. *Ecology* 81, 1177.

Falkenmark, M. (1995) Land and water linkages: a synopsis. In: FAO Land and Water Bulletin Number 1. Land and Water Integration and River Basin Management, Food and Agriculture Organization, Rome, pp, 15–16.

FAO (Food and Agriculture Organization) (1995) Digital Soil Map of the World (DSMW): based on the FAO/UNESCO Soil Map of the World, original scale 1:5,000,000. FAO-AGL, Rome.

FAO (Food and Agriculture Organization) (2001) FAOCLIM, a CD-ROM with worldwide agroclimatic data (v. 2). Environment and Natural Resources Service (SDRN) Working Papers, No. 5. FAO-SDRN, Rome.

FAO (Food and Agriculture Organization) (2003). Unlocking the water potential of agriculture. FAO, Rome.

Forner, C. and Jotzo, F. (2002) Future restrictions for sinks in the CDM: how about a cap on supply? *Climate Policy* 2, 353–365.

Gedney, N.N., Cox, P.M., Betts, R.A., Boucher, O., Huntingford, C. and Stott, P.A. (2006) Detection of a carbon dioxide effect in continental river runoff records. *Nature* 439, 835–838.

Gordon, L.J., Steffen, W., Jonsson, B.F., Folke, C., Falkenmark, M. and Johannessen, A. (2005) Human modification of global water vapor flows from the land surface. *Proceedings of the National Academy of Sciences* 102, 7612–7617.

Greenpeace (2003) Sinks of the CDM: after the climate, will biodiversity go down the drain?! Greenpeace briefing paper, 30 May 2003. Greenpeace, Bonn, Germany.

Hansen, M., DeFries, R., Townshend, J.R., Carroll, M., Dimiceli, C. and Sohlberg, R. (2003) 500m MODIS Vegetation Continuous Fields. The Global Land Cover Facility, College Park, Maryland.

Heuvelmans, G., Garcia, J., Muys, B., Feyen, J. and Coppin, P. (2005) Modelling the water balance with SWAT as part of the land use impact evaluation in a life cycle study of carbon sequestration scenarios. *Hydrological Processes* 19 (3), 729–748.

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G. and Jarvis, A. (2004) The WorldClim Interpolated Global Terrestrial Climate Surfaces. Version 1.3. Available for download at: http://biogeo.berkeley.edu/worldclim/worldclim.htm

Houghton, R.A. (1999) The annual net flux of carbon to the atmosphere from changes in land use 1850–1990. *Tellus* 51B, 298–313.

Houghton, R.A., Hobbie, J.E., Melillo, J.M., Moore, B., Peterson, B.J., Shaver, G.R. and Woodwell, G.M. (1983) Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: a net release of CO_2 to the atmosphere. *Ecological Monographs* 53, 235–262.

Huq, S. (2002) Applying sustainable development criteria to CDM projects: PCF experience. PCF*plus* Report 10. April 2002. World Bank, Washington, DC.

IPCC (Intergovernmental Panel on Climate Change) (1996) *Climate Change 1995: Impacts, Adaptation, and Mitigation of Climate Change: Scientific–Technical Analysis*. The Contribution of Working Group II to the Second Assessment Report of the Intergovernmental Panel on Climate Change. Watson, R.T., Zinyowera, M.C. and Moss, R.H. (eds), Cambridge University Press, Cambridge, UK.

IPCC (Intergovernmental Panel on Climate Change) (2000) IPCC special report on land use, land-use change and forestry. A special report of the Intergovernmental Panel on Climate Change. Approved at IPCC Plenary XVI (Montreal, 1–8 May 2000). IPCC Secretariat, c/o World Meteorological Organisation, Geneva, Switzerland.

IPCC (Intergovernmental Panel on Climate Change) (2001) *Climate Change 2001: Impacts, Adaptation, and Vulnerability*. Contribution of Working Group II to the IPCC Third Assessment Report (TAR). Cambridge University Press, Cambridge, UK.

IWMI (International Water Management Institute) (2000) World water supply and demand in 2025. In: Rijsberman, F.R. (ed.) *World Water Scenario Analyses*. World Water Council, Marseille, France, pp. 34–47.

Jung, M. (2005) Host country attractiveness for CDM non-sink projects. HWWA Discussion Paper 312. Hamburgisches Welt-Wirtschafts-Archiv (HWWA). Institute of International Economics, Hamburg, Germany.

Kolshus, H.H. (2001) Carbon sequestration in sinks: an overview of potential and costs. CICERO Working Paper 2001, Center for International Climate and Environment Research, Blindern, Norway.

Lal, R., Kimble, J. and Follett, R. (1997) Land use and soil C pools in terrestrial ecosystems. In: Lal, R., Kimble, J.M., Follett, R.F. and Stewart, B.A. (eds) *Management of Carbon Sequestration in Soil*. Advances in Soil Science. CRC Press, Boca Raton, Florida, pp. 1–10.

Lund, H.G. (2002) When is a forest not a forest. *Journal of Forestry* 100, 8, 21–28.

L'vovich, M.I. and White, G.F. (1990) Use and transformations of terrestrial water systems. In: Turner, B.L. II (ed.) *The Earth as Transformed by Human Action: Global and Regional Changes in the Biosphere Over the Past 300 Years*. Cambridge University Press, Cambridge, UK, pp. 235–252.

Maidment, D.R. (1992) *Handbook of Hydrology*. McGraw-Hill, New York.

Malhi, Y., Meir, P. and Brown, S. (2002) Forests, carbon and global climate. In: Swingland, I.R. (ed.) *Capturing Carbon and Conserving Biodiversity*. Earthscan Publications Ltd, London, pp. 15–41.

Mollicone D., Achard, F., Eva, H.D., Belward, A.S., Federici, S., Lumicisi, A., Rizzo, V.C., Stibig, H.J. and Valentini, R. (2003) Land use change monitoring in the framework of the UNFCCCC and its Kyoto

Protocol: report on current capabilities of satellite remote sensing technology. EUR 20867 EN. European Communities, Luxembourg.

Nilsson, S. and Schopfhauser, W. (1995) The carbon-sequestration potential of a global afforestation program. *Climatic Change* 30 (3), 267–293.

NIMA (National Imagery and Mapping Agency) (1997) VectorMap (VMAP) Level 1. National GeoSpatial Agency, U.S. Department of Defense, Bethesda, Maryland.

Noble, I.R. and Scholes, R.J. (2001) Sinks and the Kyoto Protocol. *Climate Policy* 1, 1–23.

Nordhaus, W.D. (1991) The cost of slowing climate change: a survey. *The Energy Journal* 12 (1), 37–65.

Oldeman, L.R. (ed.) (1991) Guidelines for general assessment of the status of human-induced soil degradation. Working Paper and Reprint 88/4. International Soil Reference and Information Centre, Wageningen, the Netherlands.

Oldeman, L.R., Hakkeling, R.T.A. and Sombroek, W.G. (1991) World map of the status of human-induced soil degradation: an explanatory note. Global Assessment of Soil Degradation (GLASOD). International Soil Reference Information Centre, Wageningen, the Netherlands, and United Nations Environment Program, Nairobi, Kenya.

Raskin, P., Gleick, P., Kirshen, P., Pontius, G. and Strzepek, K. (1997) Water futures: assessment of long-range patterns and prospects. Stockholm Environment Institute, Stockholm, Sweden.

Rijsberman, F., Bossio, D. and Noble, A.D. (2005) The impact of land degradation and improved land management on water productivity. Paper presented at the International Conference of Soil, Water and Environmental Quality – Issues and Strategies, New Delhi, India, 28 January–1 February 2005.

Rockström, J., Gordon, L., Folke, C., Falkenmark, M. and Engwall, M. (1999) Linkages among water vapor flows, food production, and terrestrial ecosystems services. *Conservation Ecology* 3, 2–5.

Running, S.W., Thornton, P.E., Nemani, R.R. and Glassy, J.M. (2000) Global terrestrial gross and net primary productivity from the earth observing system. In: Sala, O., Jackson, R. and Mooney, H. (eds) *Methods in Ecosystem Science*. Springer-Verlag, New York.

Schenk, H.J. and Jackson, R.B. (2002) The global biogeography of roots. *Ecological Monographs* 72, 311–328.

Scurlock, J.M. and Olson, R.J. (2002) Terrestrial net primary productivity – a brief history and a new worldwide database. *Environmental Reviews* 10 (2), 91–109.

Seckler, D., Amarasinghe, U., Mlden, D.J., de Silva, R. and Barker R. (1998) World water demand and supply, 1990 to 2025: scenarios and issues. IWMI Research Report 19. International Water Management Institute, Colombo, Sri Lanka.

Sedjo, R. and Solomon, A. (1989) Climate and forests. In: Rosenberg, N.J., Easterling, W.E. III, Crosson, P.R. and Darmstadter, J. (eds) *Greenhouse Warming: Abatement and Adaptation*. Resources for the Future, Washington, DC, pp. 105–119.

Shiklomanov, I.A. (1998) World water resources: an appraisal for the 21st century. International Hydrological Program, United Nations Educational, Scientific and Cultural Organization, Paris.

Smith, J. and Scherr, S. (2002) Forest carbon and local livelihoods: an assessment of opportunities and policy recommendations. Center for International Forestry Research, Bogor, Indonesia.

Stocking, M.A. (2003) Tropical soils and food security: the next 50 years. *Science* 302, 1356–1359.

Swank, W. T. and Douglass, J.E. (1974) Streamflow greatly reduced by converting deciduous hardwood stands to pine. *Science* 185, 857–859.

Thornthwaite, C. (1948) An approach toward a rational classification of climate. *Geographical Review* 38 (1), 55–94.

Thornthwaite, C. and Mather, J. (1955) The water balance. *Publications in Climatology* 8 (1), 1–104.

Torvanger, A., Alfsen, K.H., Kolshus, H.H. and Sygna, L. (2001) The state of climate policy research and climate policy. CICERO Working Paper 2001: 2. Center for International Climate and Environment Research, Blindern, Norway.

Trexler, M and Haugen, C. (1995) Keeping it green: tropical forestry opportunities for mitigating climate change. World Resources Institute and Environmental Protection Agency, Washington, DC.

UNFCCC (United Nations Framework Convention on Climate Change Secretariat) (2002) Report of the conference of the parties on its seventh session, Marrakech (Morocco), 29 October–10 November 2001. Addendum Part Two: Action Taken by the Conference of the Parties, Volumes I and II (FCCC/CP/2001/13/Add. 1). UNFCCC, Bonn, Germany.

USGS (United States Geological Survey) (1993) The Global Ecosystem Land Cover Characterization Database v. 2.0, http://edcdaac.usgs.gov/glcc/glcc.html, USGS, Earth Resources Observation System Distributed Active Archive Center. Accessed March 2005.

USGS (United States Geological Survey) (2004) SRTM Digital Elevation Data, Reprocessing by the GLCF. Reprocessed to GeoTIFF by the Global Land Cover Facility, College Park, Maryland. Version 1.0.

Verchot, L.V., Zomer, R.J., Van Straaten, O. and Muys, B. (2006) Implications of country-level decisions on the specification of crown cover in the definition of forests for land area eligible for afforestation and reforestation activities in the CDM. *Journal of Climate Change* 81 (3–4), 415–430.

Vincent, J.R. (1995) Timber trade, economics, and tropical forest management. In: Primack, R.B. and Lovejoy, T.E. (eds) *Ecology, Conservation and Management of Southeast Asia Rainforests*. Yale University Press, New Haven, Connecticut, pp. 241–261.

Vorosmarty, C.J., Green, P., Salisbury, J. and Lammers, R.B. (2000) Global water resources: vulnerability from climate change and population growth. *Science* 289, 284–288.

Wallace, J.S. (2000) Increasing agricultural water efficiency to meet future food production. *Agriculture, Ecosystems and Environment* 82, 105–119.

WDPA (World Database on Protected Areas) Consortium (2004) World database on protected areas. World Conservation Union (IUCN) and UNEP-World Conservation Monitoring Centre (UNEP-WCMC). Global Land Cover Facility: http://glcf.umiacs.umd.edu/.

WHO (World Health Organization) (2006) Water sanitation and health website: http://www.who.int/water_sanitation_health/hygiene/en/

Winjum, J.K., Brown, S. and Schlamadinger, B. (1998) Forest harvests and wood products: sources and sinks of atmospheric carbon dioxide. *Forest Science* 44, 272–284.

Wood, S., Sebastian, K. and Scherr, S.J. (2000) Soil resource condition. In: Wood, S., Sebastian, K. and Scherr, S.J. (eds) *Pilot Analysis of Global Ecosystems: Agroecosystems*. International Food Policy Research Institute and World Resources Institute, Washington, DC.

Yamagata, Y. and Alexandrov, G.A. (2001) Would forestation alleviate the burden of emission reduction? An assessment of the future carbon sink from ARD activities. *Climate Policy* 1, 27–40.

Zhou, G.Y., Morris, J.D., Yana, J.H., Yua, Z.Y. and Peng, S.L. (2002) Hydrological impacts of reafforestation with eucalypts and indigenous species: a case study in southern China. *Forest Ecology and Management* 167 (1–3), 209–222.

Zomer, R.J., Trabucco, A., van Straaten, O. and Bossio, D.A. (2006) Carbon, land and water: a global analysis of the hydrologic dimensions of climate change mitigation through afforestation/reforestation. IWMI Research Report No. 101. International Water Management Institute, Colombo, Sri Lanka.