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Climate change mitigation: A spatial analysis of global land suitability for clean development mechanism afforestation and reforestation

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Abstract

Within the Kyoto Protocol, the clean development mechanism (CDM) is an instrument intended to reduce greenhouse gas emissions, while assisting developing countries in achieving sustainable development, with the multiple goals of poverty reduction, environmental benefits and cost-effective emission reductions. The CDM allows for a small percentage of emission reduction credits to come from afforestation and reforestation (CDM-AR) projects. We conducted a global analysis of land suitability for CDM-AR carbon 'sink' projects and identified large amounts of land (749 Mha) as biophysically suitable and meeting the CDM-AR eligibility criteria. Forty-six percent of all the suitable areas globally were found in South America and 27% in Sub-Saharan Africa. In Asia, despite the larger land mass, relatively less land was available. In South America and Sub-Saharan Africa the majority of the suitable land was shrubland/grassland or savanna. In Asia the majority of the land was low-intensity agriculture. The sociologic and ecological analyses showed that large amounts of suitable land exhibited relatively low population densities. Many of the most marginal areas were eliminated due to high aridity, which resulted in a generally Gaussian distribution of land productivity classes. If the cap on CDM-AR were raised to compensate for a substantially greater offset of carbon emission through sink projects, this study suggests that it will be increasingly important to consider implications on local to regional food security and local community livelihoods.
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1. Introduction

Human activity has significantly altered the global carbon cycle as land use change and fossil fuel burning have increased levels of CO_2 in the atmosphere, causing changes in our climate at an alarming and accelerating rate (IPCC, 1996, 2001). Many factors play into the complex equation that determines the impact of greenhouse gas emissions on the concentration of these gases in the atmosphere. There are however, two strategies available to mitigate the CO_2 increase: emission reductions (i.e., reductions at the source), or increasing the plant sink of atmospheric CO_2 through photosynthesis by increasing the biomass in terrestrial ecosystems. When this carbon fixation is semi-permanent, such as in forests or recalcitrant soil organic matter, it is termed 'carbon sequestration'. Forests and trees are important components of the global C cycle as they store large quantities of carbon in vegetation and soils. However, forests are both sources and sinks of atmospheric CO_2. They release carbon to the atmosphere when disturbed by natural or human causes, and they absorb atmospheric CO_2 when vegetation and soil carbon accumulate after afforestation or natural revegetation.

International efforts to address climate change and other global environmental problems have largely been through global treaties and other policy frameworks, including such agreements as the United Nations Framework Convention on Climate Change (UNFCCC) with the Kyoto Protocol (KP), the Convention on Biological Diversity, the UN

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Framework on Forests, the Convention to Combat Desertification, and others. Each sets up institutions and mitigation measures that address global change issues and processes, and creates mechanisms which are legally binding to the signatory countries. These institutions and measures have, however, complex interactions with real world multi-process, multi-scale conditions.

In this study, we investigate the availability of suitable land for climate change mitigation activities, as per the rules of the clean development mechanism-afforestation/reforestation (CDM-AR) provisions of the UNFCCC's KP. The CDM-AR allows for carbon sequestration offsets to meet emission reduction obligations for the developed countries, through the purchase of Certified Emissions Reduction Units (CERs) from afforestation or reforestation projects in developing countries. The purpose of the CDM is to assist developing countries in achieving sustainable development, with the multiple goals of poverty reduction, environmental benefits and cost-effective emissions reductions. CDM "sink" projects require that carbon be sequestered into semi-permanent 'sinks', primarily by growing trees through afforestation and reforestation. While it is widely acknowledged that the CDM has not lived up to expectations, there is considerable optimism in developing countries and the development community that the potential investments represented by CDM-AR can be a boon for rural development and environmental protection if proper incentives can be put in place (Cosbey et al., 2005). Many countries are already involved in planning or implementing pilot projects and numerous research programs are underway to understand and delineate how best to implement CDM-AR (see http://www.joanneum.at/encofor).

Possible afforestation/reforestation activities fall into the following CDM-eligible categories:

- new, large-scale, industrial plantations;
- introduction of trees into existing agricultural systems (agroforestry);
- small-scale plantations by landowners;
- establishment of woodlots on communal lands;
- rehabilitation of degraded areas through tree planting or assisted natural regeneration;
- reforestation of marginal areas with native species (e.g., riverine areas, steep slopes, buffer zones and corridors around and between existing forest fragments);
- establishment of biomass plantation for energy production and the substitution of fossil fuels.

Related forestry activities not eligible under the CDM include forest conservation, improved forest management, reduced impact logging, and enrichment planting. Only afforestation and reforestation are accepted as eligible activities, as agreed at COP-7 in what are known as the Marrakech Accords (UNFCCC, 2002a,b). To be considered either of these, the land must not have been forested at the beginning of 1990, which is the KP baseline year.

This study delineates the potentially suitable areas for CDM-AR projects globally, and describes the socio-ecological characteristics of these suitable lands based upon a spatial analysis of biophysical and socio-economic conditions. In a companion paper to this study we present estimates of the impacts of CDM-AR on global, regional and local water cycles by applying a hydrologic spatial model to the results of this land suitability analysis (Trabucco et al., 2008). The suitability of CDM-AR projects, as per the current proposed guidelines for their application in developing countries (these countries are referred to as Non-Annex I countries in the KP), is constrained by the current UNFCCC guidelines for CDM-AR projects within the first commitment period (2007–2012), the definitions adopted for forest and forestry activities by individual countries, and a complex of biophysical and socio-economic factors necessary for a sustainable, socially equitable, and economically viable tree growing enterprise. Two main factors are reconciled in our analysis:

- The need to conform to the specific guidelines and regulations of the UNFCCC (e.g., the definition of forest, but also explicitly articulated concerns about food security, sustainability and environmental conservation).
- Suitability of the biophysical environment to support relatively robust biomass production (i.e., fixation of CO_2) to make the projects viable and economically feasible.

2. Materials and methods

2.1. Land suitability analysis

Land suitability for CDM-AR was modeled, as per the existing rules of the first commitment period (2007–2012). In addition, socio-ecological characteristics of these suitable areas are described, including current land use, population levels and ecosystem characteristics of these lands.

2.2. Spatial modeling and datasets

A spatial modeling procedure was developed and implemented in ArcGIS (ESRI Inc.) using ArcAML programming language, This was used to identify areas meeting a range of suitability criteria. All areas that were deemed not suitable for CDM-AR due to the environmental and land use factors have been excluded a priori from our analysis. In addition, forested and recently deforested areas ineligible under current UNFCCC rules were also excluded:

- drier arid/semi-arid areas with Aridity Index less than 0.65 ($AI < 0.65$);
- high elevation areas, above 3500 m and/or timberline;
- areas covered by water bodies;
- urban areas;

- areas classified as various types of tundra;
- areas classified as irrigated or under other intensive agricultural production, assuming that these areas are already in high value production or their conversion may impact on food security;
- currently forested areas that are ineligible due to UNFCCC rules;
- recently deforested areas that are ineligible due to UNFCCC rules.

Environmental and other global geospatial datasets used for the global analysis (spatial resolution: 500 m–1 km/15–30 arc-seconds) include:

- VMAP 1—Country Boundaries (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 on Protected Areas (WDPA Consortium, 2004)
- WorldClim (Hijmans et al., 2004)
- Gridded Population of the World (2000) (CIESIN and CIAT, 2005)
- MOD17A3—MODIS Net Annual Primary Production (Running et al., 2000)
- GLASOD—Global Assessment of Soil Degradation (Oldeman et al., 1991)

All datasets used for the analyses have been re-projected into two coordinate systems, sinusoidal and geographic. The sinusoidal projection has been used to calculate zonal statistics and carry out areal computations as it represents area extent accurately across latitudes (i.e., equal-area projection). The cell size for analyses in sinusoidal projection is 500 m. The dataset in geographic coordinates is used for map presentation purposes. The results of the land suitability analysis have been mapped and tabulated on a global, regional, and national basis.

The Global Ecosystem Land Cover Characterization Database (USGS, 1993) was used to delineate areas which were classified as forest, i.e., in 1991 (the CDM baseline year). The MODIS Vegetation Continuous Fields (VCF) dataset (Hansen et al., 2003), a global dataset of tree canopy cover extracted from multi-temporal MODIS data (500 m resolution), was used to identify currently forested areas within the remaining ‘‘non-forest areas’’. A threshold of 30% canopy cover was used as the forest definition, as per results of an earlier analysis of the impact of forest definition on areas available at a national scale (Verchot and Zomer, 2007). Additionally, ‘‘recently deforested areas’’ were identified by comparing the VCF with the USGS (1993) data. However, the varying resolutions and classification system of the respective datasets introduces incongruencies when the two are directly compared, so that the identification of deforestation is very much only a rough estimate with a wide range of error.’’

Areas above or approaching timberline were considered unsuitable and were delineated as areas with average temperature below 6.5 °C (Korner and Paulsen, 2004), over the length of growing season, as calculated from the WorldClim dataset (Hijmans et al., 2004). Although tree-line can surpass 4000 m in certain parts of the world, CDM projects are here assumed to be unrealistic at elevations above 3500 m because of slow tree growth rates. Thus, additionally all land above 3500 m (based on the SRTM DEM) was excluded.

2.3. Aridity Index

Usually aridity is expressed as a function of precipitation, potential evapotranspiration (*PET*), and temperature. In a classification of climatic zones proposed by UNEP (1997), the Aridity Index (AI) is used to quantify precipitation deficit over atmospheric water demand as:

$$\text{Aridity Index (AI)} = \frac{\text{MAP}}{\text{MAE}} \tag{1}$$

where MAP is the mean annual precipitation and MAE is the mean annual evapotranspiration.

Monthly values for precipitation and temperature were obtained from the WORLDClim dataset (Hijmans et al., 2004) for years 1960–1990, at a resolution of 30 arc-seconds, or ~1 km at equator. MAE was estimated based on a global modeling of PET (Trabucco et al., 2008) using a spatialized implementation of the Hargreaves (1994) evapotranspiration equation. The global AI dataset (1 km resolution) produced in the analysis (Fig. 1) was compared to the USGS Land Characteristics Database (USGS, 1993), and the MODIS Tree Cover Percentage (Hansen et al., 2003) estimates, to obtain an AI threshold. Optimal bioclimatic conditions for CDM-AR were defined as having a minimum threshold as $AI > 0.65$, using an iterative method of comparison with the land use and tree cover datasets (Zomer et al., 2006), across a range of biomes and agro-ecological zones. This threshold for suitability represents a moisture range generally observed in semi-arid zones (UNEP, 1997) that can support rain-fed agriculture with more or less sustained levels of production.

2.4. Net primary productivity

The MODIS/Terra Annual Net Primary Production dataset (MOD17A3) was obtained from the USGS Eros Data Center. MOD17A3 Total Gross Primary Productivity is computed using the amount of photosynthetically active radiation (PAR) measured by the MODIS instrument. Heinsch et al. (2005) have shown good correlation ($r^2 = 0.859 \pm 0.173$) between NPP estimated by MOD17A3 and 38 site-years of NPP measurements. Other studies have demonstrated the absence of systematic under- or over-

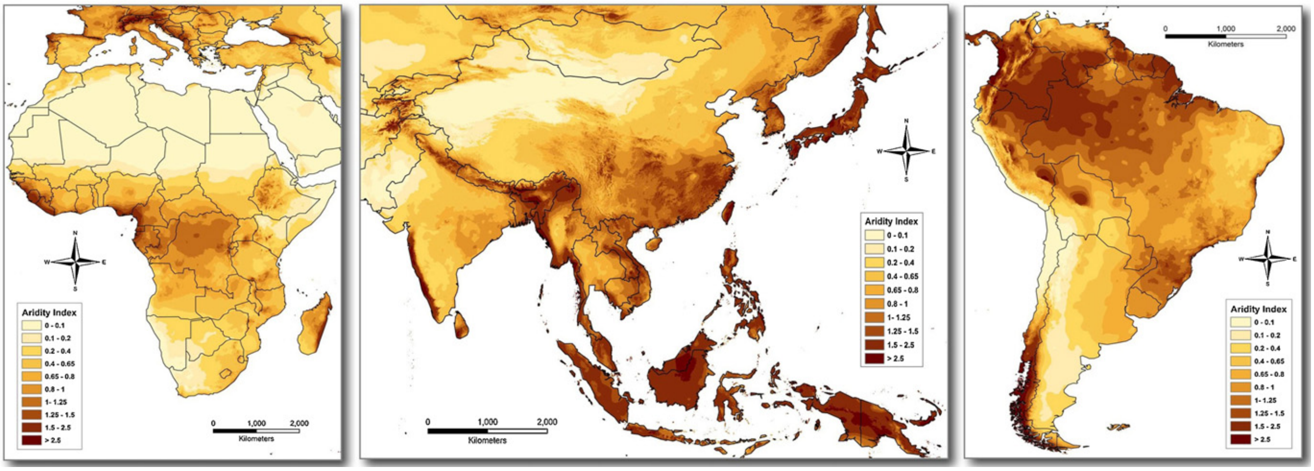

Fig. 1. Aridity Index (AI) was calculated for the entire globe. Aridity maps for South America and Africa are shown below. A threshold value of AI > 0.65 was used as a parameter in the land suitability analysis to delineate CDM-AR suitable areas. Note that higher AI and darker color represents more humid conditions, with low AI and lighter colors representing higher aridity (data source: Hijmans et al., 2004).

estimation across different biomes compared to field observed NPP (Zhao et al., 2005; Turner et al., 2003). In our analysis, annual NPP grids over the period between 2000 and 2004 have been aggregated into one average annual NPP dataset and used to analyze the current productivity of land deemed suitable for CDM-AR.

2.5. Land degradation

To explore the potential of CDM-AR to contribute meaningfully to sustainable development, and specifically to the large scale problem of on-going land degradation, the land suitability analysis was overlaid with the global assessment of human-induced soil degradation (GLASOD) spatial dataset to delineate severity of land degradation within suitable areas. The GLASOD is based primarily on expert judgment (Oldeman, 1991; Oldeman et al., 1991), and currently is the only available global assessment of land degradation. It is at a very coarse resolution (1:10 M), makes broad generalizations spatially, and tends to highlight only 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. However, many global interpretations are based on GLASOD, or derived products, as no other database is currently available at the global scale. Given that proviso, to analyze 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, where the units represent both the degree of degradation and the extent of that degradation within the mapping unit. Area estimations are made using degradation DEGREE (light, moderate, strong and extreme), by initially calculating 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.

3. Results and discussion

3.1. Lands suitable for CDM-AR

Globally more than 760 Mha of land were found to be suitable for CDM-AR activities, meeting a minimal set of eligibility criteria, both statutory and biophysical (Fig. 2). This represents just over 9% of total land surface area of all Non-Annex I countries. Global totals in this paper are reported as the sum of six regions, which cover most of the countries with significant CDM-AR potential, leaving out some countries in Europe and Central Asia which together comprise a very small percentage of suitable land. Within these six regions, 749 Mha of land was initially identified as biophysically suitable. These results compare well with earlier studies that have asked the question how much land is available for reforestation (Winjum et al., 1998; Nilsson and Schopfhauser, 1995; Trexler and Haugen, 1995) and what is the potential carbon sequestration (Yamagata and Alexandrov, 2001; Noble and Scholes, 2001; Vrolijk and Grubb, 2001; see Jung, 2005 for an extensive listing by country). In these global studies, the area available for tree plantations is variably estimated at 345 Mha (Nilsson and Schopfhauser, 1995), 465 Mha (Sedjo and Solomon, 1989), and 510 Mha (Nordhaus, 1991). Nilsson and Schopfhauser (1995) and Trexler and Haugen (1995) were designated by the IPCC

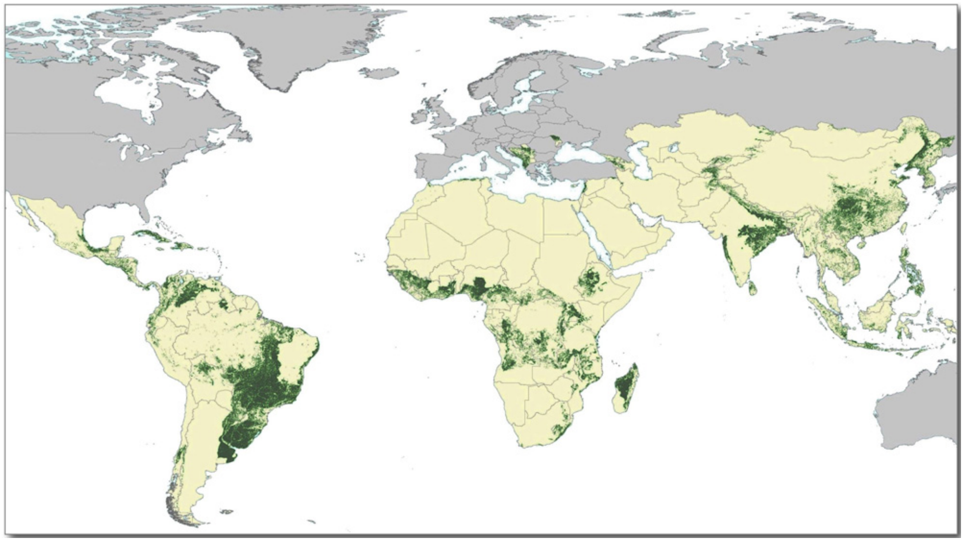

Fig. 2. Global map of CDM-AR suitable land (dark green) within Non-Annex I countries (light yellow), as delineated by the land suitability analysis. A 30% crown cover density threshold was used to define forest, and protected areas are not included. Annex I countries are shown in grey (data sources: NIMA, 1997; USGS, 1993; Hansen et al., 2003; USGS, 2004; WDPA Consortium 2004; Hijmans et al., 2004).

Second Assessment Report (Brown et al., 1996) as suitable studies for global analysis of the mitigation potential of forests, including afforestation/reforestation. The two studies together suggest that ~700 Mha of land could be available for carbon sequestration and conservation, globally, including 138 Mha for avoided tropical deforestation, 217 Mha for regeneration of tropical forests, and 345 Mha for plantations and agroforestry. Sathaye and Ravindranath (1998) suggest that 300 Mha may be available for mitigation in 10 tropical and temperate countries in Asia, including 181 Mha of degraded land for plantation forestry, and 79 Mha of degraded forestland for regeneration. In our study, large tracts of suitable land are found in South America (46% of all the suitable areas globally) and Sub-Saharan Africa (27%), reflecting the greater landmass of these regions, and to a certain extent, lower population densities. The three Asian regions together comprise only about 200 Mha, compared to more that 330 Mha in South America and almost 200 Mha in Africa. Within the respective regions, the amount of available land ranged from 8% of the total land surface area in Southeast Asia, to more than 19% of South America.

As our suitability estimates are based exclusively on biophysical criteria combined with UNFCCC requirements, they represent an over-estimation of actual areas available. Areas that might be available for CDM-AR, in reality, depend upon a more complex set of parameters within a national, local and site-specific socio-economic and ecological context. These conditions go beyond CDM-AR rules and tree growth characteristics, to include such factors as land opportunity costs, access to markets, land and tree tenure, or national level infrastructure and support. A substantially smaller proportion of this identified suitable area will meet the more specific criteria required to consider CDM-AR a viable option for landowners, land managers, communities, and/or national planners. To understand the socio-economic conditions and ecological characteristics of these areas, and to better judge the likelihood of CDM-AR projects being realized, lands identified by the global analysis as suitable were characterized by existing land use, population density, elevation, aridity, productivity, and severity of land degradation (Fig. 3).

3.2. Land use

Across five of the six regions – the exception being Sub-Saharan Africa – cropland made up half or more of the suitable land, constituting more than 364 Mha (Table 1). In Sub-Saharan Africa, the majority of the available land is savanna (Fig. 4). The high suitability of agricultural land is not surprising as tropical deforestation is largely driven by the needs of agriculture. While intensive production land has been excluded from this analysis, subsistence and low-intensity agricultural areas are ideal candidate sites, where there are deep soils, an appropriate climate, and adequate moisture. Additionally, these sites meet the CDM-AR criteria as they are not currently forested. However, the probability that some of this area will actually be converted to CDM-AR is dependent on socio-economic and local food security issues. In this regard, this estimate should be considered a theoretical potential for land suitability (Cannell, 2003).

In both South Asia and Southeast Asia a high percentage of the land that is identified as suitable for CDM-AR is agricultural land (76%), with much smaller areas of shrubland and savanna, reflecting high population densities and extensive areas of agricultural production in these regions. In addition, much of the hilly land in South Asia and the Himalayan foothills have canopy cover above the 30% threshold for forest, although many of these areas are

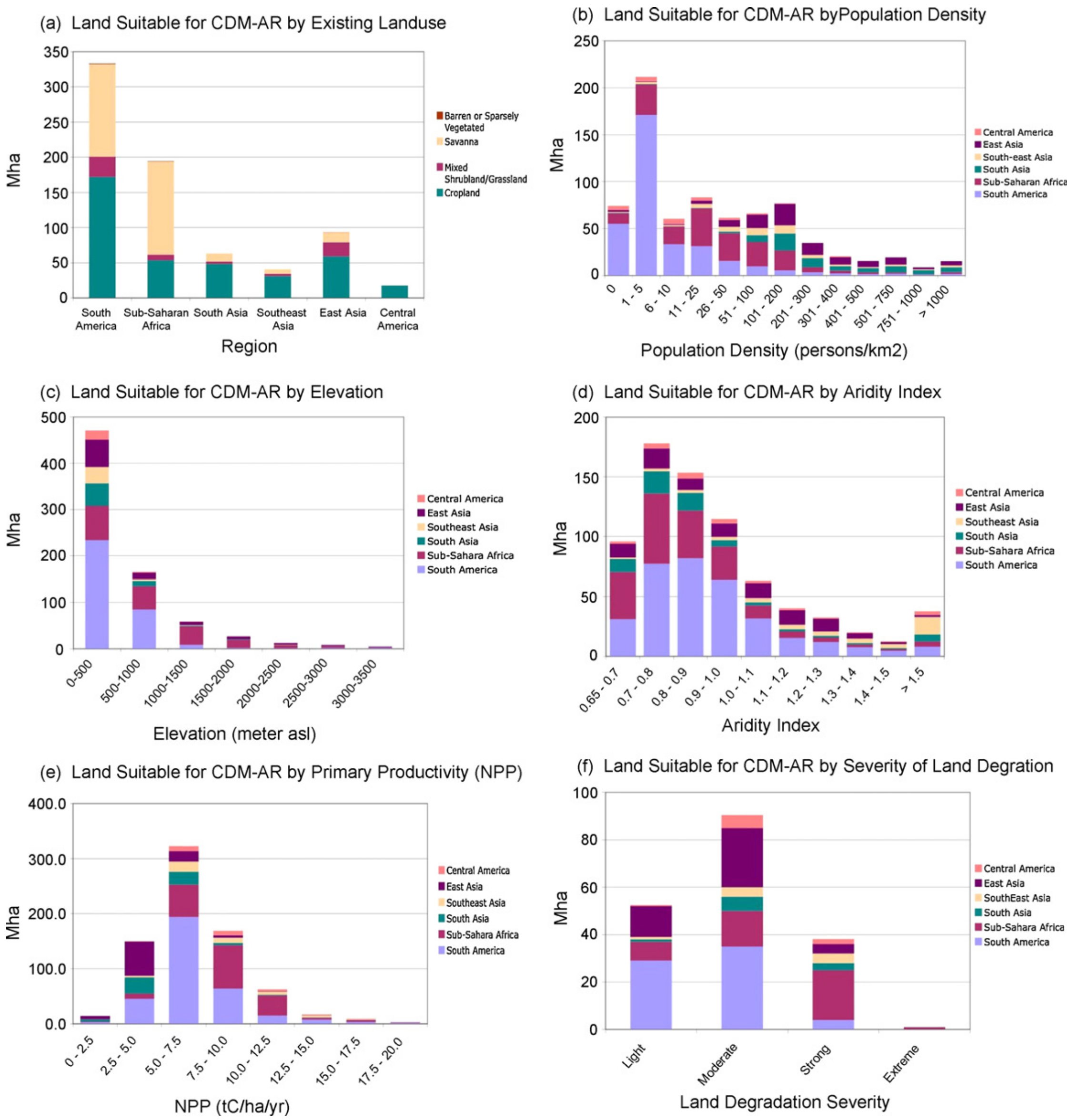

Fig. 3. Socio-ecological characteristics of CDM-AR suitable areas: (a) existing land use type; (b) population density (persons km^{-2}); (c) elevation (meters asl); (d) Aridity Index (AI); (e) net primary productivity (NPP) (tC ha^{-1} yr^{-1}); (f) severity of land degradation.

actually under various forms of intensive agricultural production. This demonstrates the constraints associated with a forest definition for the CDM that uses only a crown cover criterion for determining forest land and does not include a land use component in the definition (Verchot and Zomer, 2007).

More than 52% (172 Mha) of the land in South America identified as suitable is classified as cropland. An additional 29 Mha is mixed shrubland/grassland, and is likely to be under some form of livestock production activity. Since the AI was set at a threshold that generally indicates a lack of water stress, these included mesic savanna areas that are fairly productive. Sub-Saharan Africa has a large amount of savanna (132 Mha) classified as suitable (68%), where it is likely that extensive pastoralist and other subsistence livelihood activities are present, even in less populated areas. These semi-arid lands have a potential for agroforestry and other options beside tree plantations for increasing carbon stocks. Restoration of dry forest, for example addressing losses of these ecosystems in Ethiopia, Madagascar, or Central America, can have significant potential for sequestering carbon over the long term despite exhibiting slow tree growth. These results also suggest that the opportunity cost of land for CDM in Sub-Saharan Africa is likely to be lower than elsewhere in the world, although intangible biodiversity and environmental service values may need to be accounted for, as in the case of wildlife habitat or biological refugia.

Protected areas and national parks were excluded in this analysis. However, we recognize that some degraded areas now designated as protected offer optimal opportunities for reforestation and CDM-AR. A relevant example is the Mt.

Table 1
CDM-AR suitable land by existing land use type, by total area (Mha), and percent (%) of the total suitable land, regionally and globally (data source: USGS, 1993)

Region	Existing land use type								
	Cropland		Mixed shrubland/ grassland		Savanna		Barren/sparsely vegetated		Total
	Mha	%	Mha	%	Mha	%	Mha	%	Mha
Central America	18	74	3	13	3	13	0	0.1	24
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
SouthEast Asia	31	76	3	8	6	16	0	0.2	41
Global	364	50	63	9	296	41	2	0.2	749

Elgon Reforestation Project (FACE, 1998) in eastern Uganda. The government of Uganda worked with the FACE (Forests Absorbing Carbon Emissions) to fund reforestation, based on the carbon sequestration component of the improved ecosystem services provided by ecosystem restoration. The legal commitment to permanency provided by the national park status provided an ideal opportunity for C sequestration. Approx. 27 Mha of additional suitable land was identified within protected areas.

3.3. Population density

Patterns of rural population densities on suitable land vary widely between regions (Fig. 5). Population density is considered to be a measure of land utilization and it is assumed that less land is likely to be converted to tree plantations in areas with higher densities (although the amount of trees within the landscape may increase). Competition for food production and food security issues will limit adoption of CDM-AR. Globally, more than 50% of all identified areas have low population densities (<25 peo-people km^{-2}), and more than 35% of the land has densities <5 people km^{-2} (Table 2). Areas in South America have the lowest population levels, with 95% of all identified areas having <100 people km^{-2}, and almost 70% <5 persons km^{-2}. Sub-Saharan Africa has less empty lands, but still has relatively low population densities associated with these areas. More than 85% of all areas identified in Sub-Saharan Africa have <100 persons km^{-2}. In contrast, East Asia has 55% of its identified areas with population levels >100 people km^{-2}, with 11% >500 people km^{-2}. Likewise, South Asia has more than 65% of identified areas with population levels >100 persons km^{-2}, and 24% >500 persons km^{-2}. Southeast Asia has 65% of identified areas with population levels >100 persons km^{-2}, and 33% with <25 persons km^{-2}. Much of the low population density classes in South America and Sub-Saharan Africa are comprised of savanna, although particularly in South America, substantial areas of very low population density are classified as agricultural land. In Southeast Asia, degraded forest areas account for much of the low density areas. In South Asia, cropland accounts for the majority of identified areas across all population density levels.

3.4. Productivity of suitable lands

Lands identified as suitable for CDM-AR generally fall into low to moderate productivity categories (Fig. 6). This is

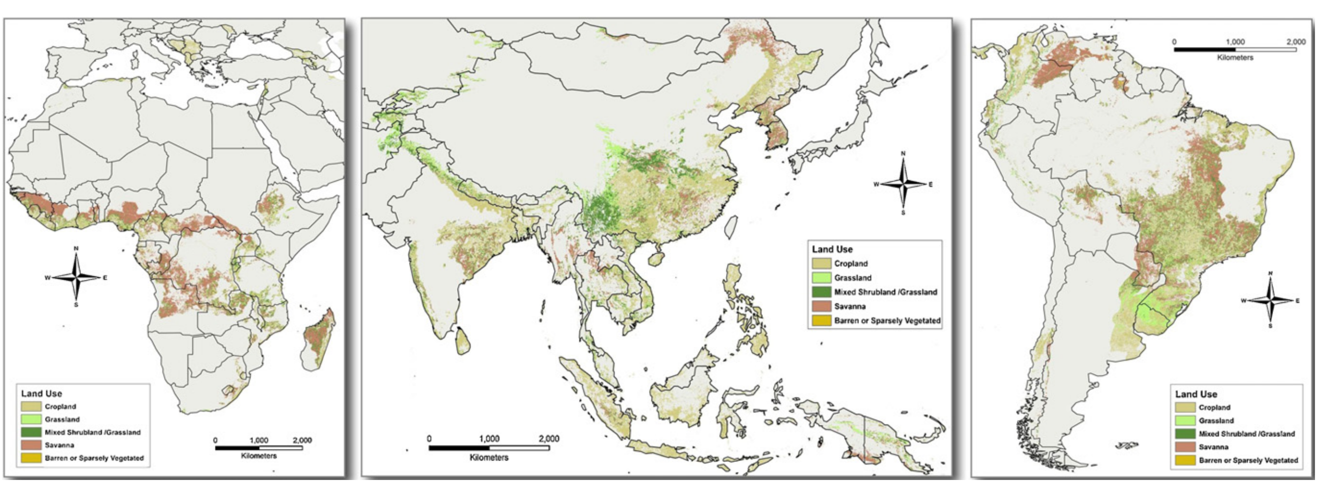

Fig. 4. Existing land use within areas identified as suitable for CDM-AR (data source: USGS, 1993).

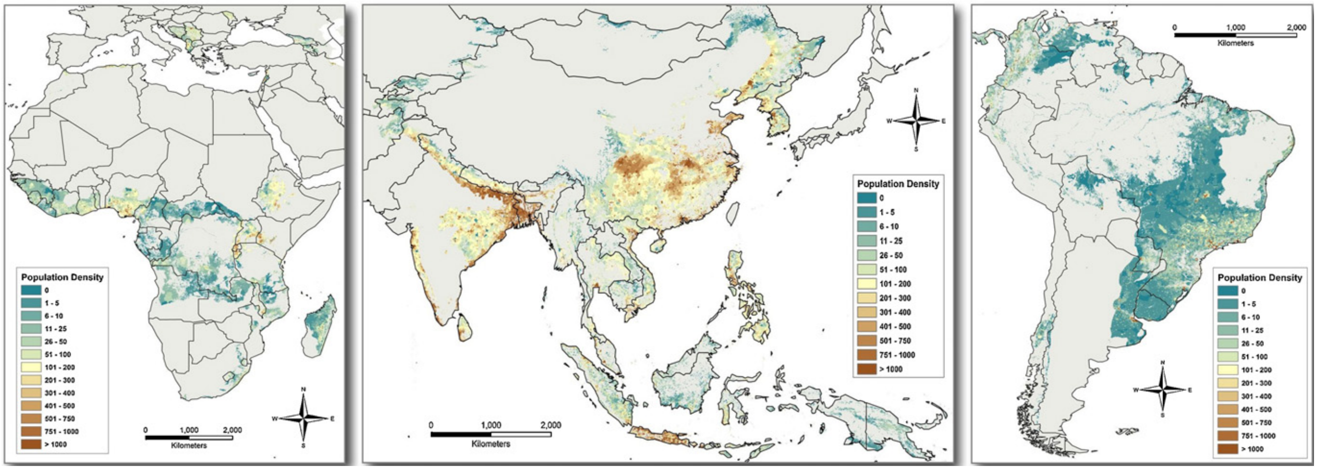

Fig. 5. Population density within areas identified as suitable for CDM-AR (data source: CIESIN and CIAT, 2005).

almost by definition because higher productivity lands are mainly intensive and irrigated cropping and forested areas, which are either ineligible or were eliminated from the analysis by our own criteria. The fact that lands are currently less productive than some of these areas does not mean that they are inherently unproductive. Large areas in agricultural landscapes are degraded (Smaling et al., 1997; Sanchez et al., 1997), but have the potential for restoration with appropriate nutrient and water management. Many of the most marginal areas were eliminated by the AI criteria, which resulted in a generally Gaussian distribution of productivity classes, centered on a moderately productive median. Globally, 88% of all available land had a NPP below 10 tC ha^{-1} yr^{-1} (Table 3). About 75% of available land in Africa and Southeast Asia, and almost all available land in South America (92%), South Asia (96%) and East Asia (98%), indicated a NPP <10 tC ha^{-1} yr^{-1}. 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. This suggests that CDM-AR funding might be appropriate for land rehabilitation schemes that improve low or unproductive land through tree-based or agroforestry production systems (Verchot et al., 2006).

3.5. Land degradation

Globally GLASOD estimates that human-induced degradation of land has occurred on 15% of the world's land area (13% light and moderate, 2% severe and very severe), mainly resulting from erosion, nutrient decline, salinization

Table 2
CDM-AR suitable land by population density, by area (Mha) and as the percent (%) of the Total CDM-AR suitable land regionally and globally (data source: CIESIN and CIAT, 2005)

Region	Population density (persons km^{-2})								
	0–10	11–25	26–50	51–100	101–200	201–300	301–400	401–500	>500
CDM-AR suitable land area (Mha)									
Central America	4	5	6	3	2	1	1	0	1
East Asia	4	4	7	14	23	13	8	6	14
Sub-Saharan Africa	63	40	30	26	21	5	3	2	4
South America	260	31	15	10	5	4	2	2	5
South Asia	1	0	2	7	18	10	5	4	16
South-east Asia	5	4	5	7	9	3	2	1	5
Global	336	85	65	68	79	36	20	16	45
Percent of total regional CDM-AR suitable land area									
Central America	18	20	23	15	10	6	3	1	5
East Asia	4	4	8	15	25	14	8	7	15
Sub-Saharan Africa	32	21	15	13	11	3	2	1	2
South America	78	9	5	3	2	1	1	0	1
South Asia	2	1	3	12	29	15	7	7	25
South-east Asia	11	10	13	18	21	8	4	3	11
Global	45	11	9	9	10	5	3	2	6

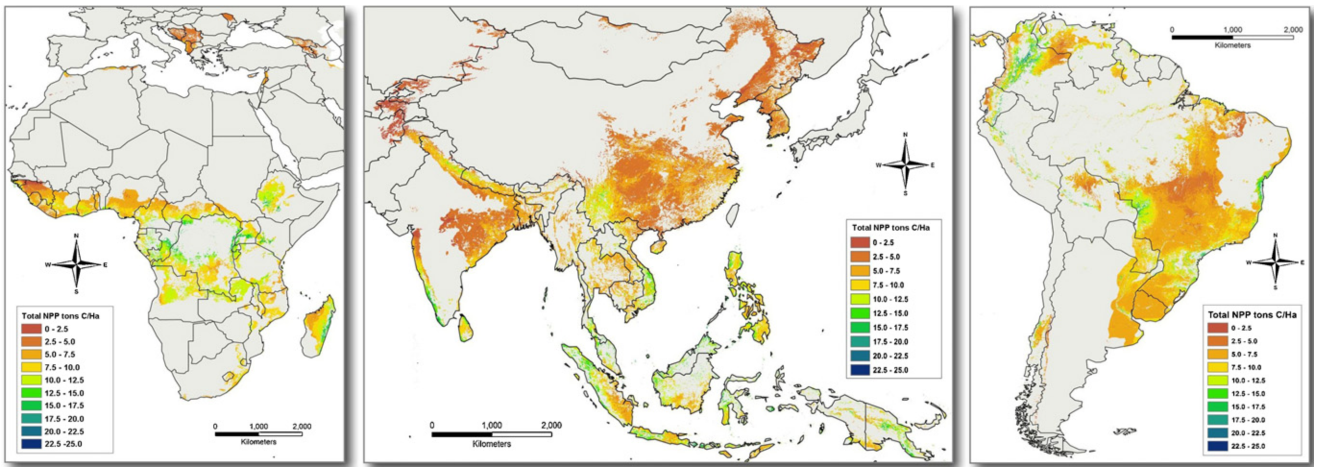

Fig. 6. Net primary productivity (NPP) within areas identified as suitable for CDM-AR (data source: Running et al., 2000).

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 land suitability analysis classifies approximately 25% of the identified CDM-AR potential areas as affected by some degree of degradation (Fig. 7 and Table 4). More than 20% of all the land identified in East Asia, South Asia, and Southeast Asia combined, falls into the moderate and strong degradation severity categories (Fig. 2). 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.

Given the large amount of land identified as suitable for CDM-AR within GLASOD degraded land classes, it is likely that afforestation, agroforestry, and conservation techniques using trees have substantial scope to contribute significantly towards addressing global land degradation issues. However, the question remains 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 on-going light degradation, although these lands are also considered to have reduced productivity. They therefore

Table 3
CDM-AR suitable land by net primary productivity (NPP), by area (Mha), and as percent (%) of the total suitable land regionally and globally (data source: Running et al., 2000)

Region	NPP productivity (tC ha^{-1} yr^{-1})							
	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
CDM-AR suitable land area (Mha)								
East Asia	6.1	62.2	19.3	4.3	1.0	0.4	0.0	93
Sub-Sahara Africa	1.5	9.2	58.9	78.9	36.7	4.0	5.3	195
South America	2.7	45.5	193.9	63.9	14.7	7.2	5.3	333
South Asia	3.9	29.7	23.3	4.1	1.3	0.6	0.3	63
South-east Asia	0.2	2.7	18.1	9.5	5.6	3.6	1.2	41
Global	14	149	314	161	59	16	12	725
Percent of total regional CDM-AR suitable land area								
East Asia	7	67	21	5	1	0	0	
Sub-Saharan Africa	1	5	30	41	19	2	3	
South America	1	14	58	19	4	2	2	
South Asia	6	47	37	7	2	1	1	
South-east Asia	0	7	44	23	14	9	3	
Global	2	21	43	22	8	2	2	

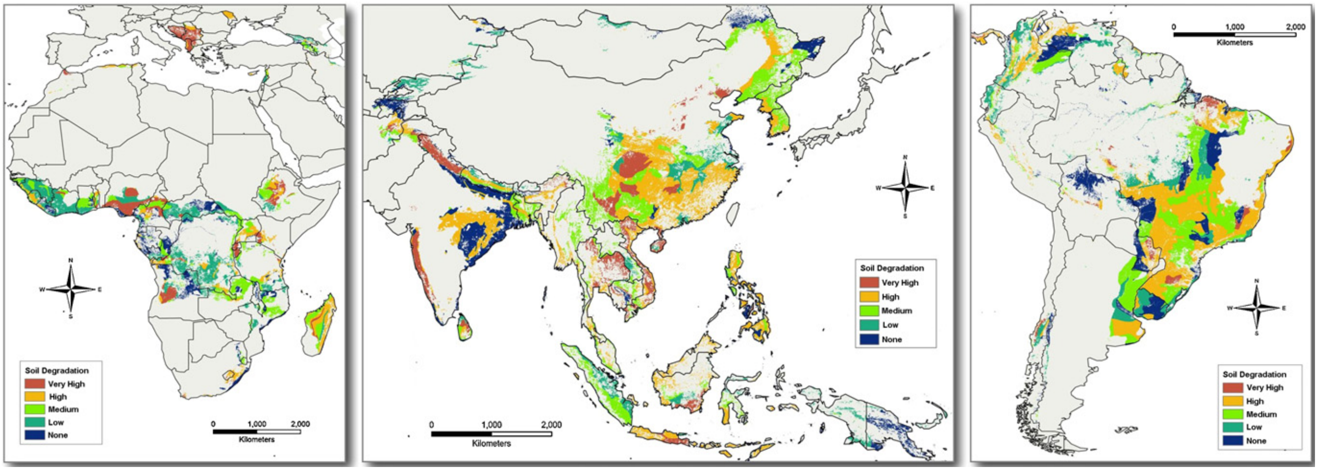

Fig. 7. Severity of soil degradation with areas identified as suitable for CDM-AR (data source: Oldeman et al., 1991).

also suffer from the disadvantage of finding it harder to provide return 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 (Verchot, 2006b; Kandji et al., 2006). 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 small holder and subsistence farming systems as represented in the mixed rain-fed farming category, and exhibit on-going degradation, ranging from soil erosion to nutrient depletion. 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 within the larger mixed farming landscape (http://www.planvivo.org). Likewise, on-going work in W. Kenya funded by GEF (World Bank, 2005) attempts to quantify the potential carbon sequestration benefits of improved farming and increased soil organic matter on small holder farms, in addition to the inclusion of trees in the farming system and the landscape.

Table 4
CDM-AR suitable land degradation severity class, by area (Mha), and as percent (%) of the total suitable land regionally and globally (data source: Oldeman et al., 1991)

Region	Soil degradation severity				
	Low	Light	Moderate	Strong	Extreme
CDM-AR suitable land area (Mha)					
Central America	15.9	0.5	5.4	2.2	0.0
East Asia	51.6	13.4	24.6	3.8	0.0
Sub-Saharan Africa	149.9	8.0	15.2	21.0	0.5
South America	265.9	28.8	34.7	3.7	0.0
South Asia	52.7	0.9	6.4	3.3	0.0
South-east Asia	31.5	1.5	4.4	3.5	0.0
Global	567	53	91	37	0
Percent of total regional CDM-AR suitable land area					
Central America	66	2	23	9	0
East Asia	55	14	26	4	0
Sub-Saharan Africa	77	4	8	11	0
South America	80	9	10	1	0
South Asia	83	1	10	5	0
South-east Asia	77	4	11	9	0
Global	76	7	12	5	0

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 that 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, referred to as Reduced Emissions from Deforestation and forest Degradation (REDD), of providing off-set credit for not cutting existing forests, and/or for improving degraded forest, has significant potential to impact positively on-going land degradation trends. The opportunities for forest landscape restoration globally are significant and can have a large impact not only on land degradation, sedimentation, and water cycles, but can provide many benefits for biodiversity conservation. The potential of these benefits are not currently included in CDM-AR, and it is very much dependent on the details and the final shape of the 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.

3.6. National level land suitability analysis and socio-ecological characteristics

The land suitability analysis was delineated, mapped and tabulated for all Non-Annex I KP signatory countries. Results of these analyses are interactively available on-line for each country using the ENCOFOR CDM-AR Online Analysis Tool (Zomer et al., 2004), available at http://csi.cgiar.org/encofor/forest/. Results are given on a country-by-country basis, with maps, tables, and graphs of the delineated area and its socio-ecological characteristics presented. The tool allows the user to specify the crown cover threshold to be used as 'forest definition' (Verchot and Zomer, 2007), and to include protected areas within the area deemed suitable for CDM-AR.

3.7. Land required to meet the CDM-AR cap

Including CDM-AR activities into the KP has been one of the 'crunch issues' in the climate negotiations, and has spawned much debate (Noble and Scholes, 2001). In addition to the basic controversy with regards to the effectiveness of CDM-AR to mitigate GHG emissions, controversial issues include measurement of carbon sequestration, permanence, leakage, land conflicts and environmental considerations (Schlamadinger and Marland, 2000; Torvanger et al., 2001), as well as various technical and scientific aspects of carbon sequestration in agriculture and forestry examined by the Special IPCC Report (IPCC, 2000) commissioned by the Subsidiary Body for Scientific and Technological Advice (SBSTA of the UNFCCC), after the Sixth Conference of the Parties (COP-6) held in Bonn in 2001. Afforestation and reforestation are currently the only eligible land use, land use change and forestry (LULUCF) activities under Article 12 of the KP (Brown et al., 2002). The Marrakech Accords (UNFCCC, 2002a, 2002b) specifically exclude activities such as avoided deforestation, improved forest management, or agricultural activities that build up soil carbon, such as conservation farming. Eligible projects have to represent a real land use change from non-forest to forest or agroforestry, thus preventing current forests being converted into plantations (Smith and Scherr, 2002).

In response to widespread concerns that CDM-AR would impact negatively on CO_2 emission reduction aims (Greenpeace, 2003), a cap on CDM-AR emission reduction offsets was set at 1% of the total global emission reduction target. The limit on the annual flow of Certified Emissions Reductions (CERs) under Article 12 is estimated to allow between 32.6 Mt C (Kolshus, 2001) and 37.4 Mt C (Mollicone et al., 2003) to be offset through CDM-AR, representing between 120 and 137 Mt CO_2 equivalents per year. In order to make a rough estimate of the amount of land that would be required to fully meet this cap, we used an averaged estimate for annual carbon sequestration (4–8 tC ha^{-1} yr^{-1}), based on a literature survey of tropical tree plantation growth rates and IPCC estimates (IPCC, 2000). The calculation indicates that from 4 to 8 Mha of land planted with fast growing tree species will easily satisfy the total allowable demand for CERs. This estimate excludes the C baseline of existing land uses, and assumes a lower productivity for marginal or degraded areas which are likely to have projects which will be less productive than typical intensively managed commercial tree plantations. This is a relatively small figure, representing less than 1–2% of the area we have identified as suitable, indicating that CDM-AR is likely to be relatively small compared to globally suitable area estimates if the 1% cap remains in place after 2012. Although small compared to the total global suitable area estimate, the total amount of land, and the potential funds made available for development, could be significant, both locally and nationally, depending upon rate of adoption, and especially dependent upon the market price for CERs.

4. Conclusion

This study highlights that there is potentially an abundance of land available for climate change mitigation by carbon sequestration in terrestrial ecosystems through afforestation and reforestation. The global impact of deforestation driven largely by agricultural expansion is a major component of ongoing global environmental change that contributes significantly to atmospheric greenhouse gas accumulation and climate change. Carbon sink projects, however, continue to be controversial (Kolshus, 2001; Kolshus et al., 2001; Forner and Jotzo, 2002; Jung, 2003). If the cap on CDM-AR were raised to compensate for a substantially greater offset of carbon emission through sink projects, this study suggests that it will be increasingly important to consider implications on local to regional food security and local community livelihoods. Increased biofuel production may also exacerbate this situation through increased competition for land resources.

The potential for smallholder farmers and rural communities to participate in CDM-AR has been highlighted and promoted by developing countries and NGOs. In particular, the adoption of agroforestry practices has been proposed as a way for smallholder farmers and communities to participate in CDM-AR projects. This could significantly increase carbon sequestration within rural and agricultural landscapes, while contributing positively to increased food security and climate change adaptation. CDM-AR rules do not currently encourage, or make it easy to promote these types of small scale, small holder, less intensive approaches, and it is more likely that much of CDM-AR projects will be in the form of fast-growing timber plantations. In many areas, food security may not be an issue, certainly not regionally or nationally. However, in areas with insecure or highly unequal tenure rights, in systems where large numbers of tenant farmers may be displaced due to the lower labor requirements of forestry activities, or access to land by indigenous communities may be lost, the displacement of subsistence farming activities may be of high concern (Smith and Scherr, 2002). In contrast, examples of poplar-based agroforestry from northern India (Zomer et al., 2007) demonstrate that small-scale wood plantations and agroforestry can substantially increase carbon stocks and take pressure off nearby forests, with significant positive benefits for rural communities. In this case, afforestation provides added security to small farmer livelihoods by offering alternate production opportunities and diversification.

It is evident that the supply of potentially available land, and consequently the potential supply of carbon which can be sequestered, is far greater than what is permitted by the current cap on CDM-AR credits. It is likely that CDM-AR, and possibly other carbon sink approaches will play a larger, increasingly important role in the future, most probably starting in the second KP commitment period. This analysis shows that the potential for carbon sequestration by sink projects is great. Current negotiations also bring up the prospect of innovative approaches, which could include avoided deforestation, restoration of degraded forests, improved forest management, and/or conservation agriculture, so that credits available from sink projects will increase.

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