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101

Carbon, Land and Water:
A Global Analysis of the Hydrologic Dimensions of Climate Change Mitigation through Afforestation/Reforestation

Robert J. Zomer, Antonio Trabucco, Oliver van Straaten
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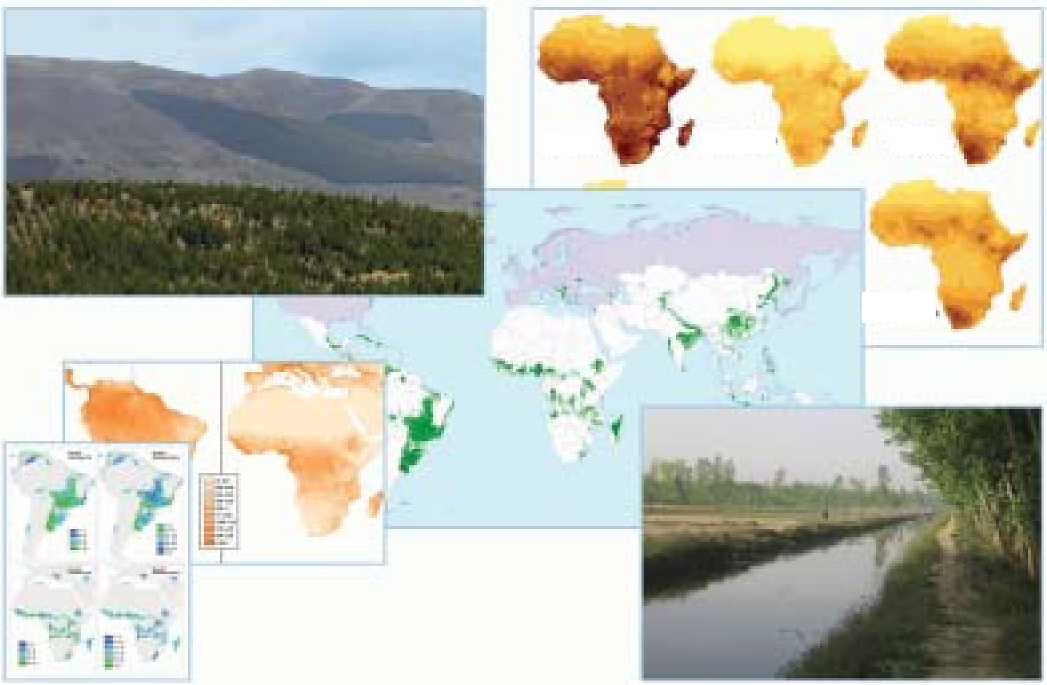

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Cover photographs by Robert Zomer and Oliver van Straaten. Geospatial analysis of carbon, land, and water under the Kyoto Protocol's Clean Development Mechanism afforestation/reforestation provisions has been combined with fieldwork and case studies to develop land suitabilty models and provide estimates of hydrologic impacts.

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Contents

Acronyms

AI	Aridity Index
AR	Afforestation/Reforestation
CDM	Clean Development Mechanism
CDM-AR	Clean Development Mechanism - Afforestation/Reforestation
CER	Certified Emissions Reduction
COP	Conference of the Parties to the UNFCCC
DEM	Digital Elevation Model
FAO	Food and Agriculture Organization of the United Nations
GHG	Greenhouse Gas
GIS	Geographic Information System
GLCF	Global Land Cover Facility (University of Maryland)
IPCC	Intergovernmental Panel on Climate Change
ISLSCP	International Satellite Land-Surface Climatology Project
IUCN	World Conservation Union (*formerly* International Union for the Conservation of Nature and Natural Resources)
IWMI	International Water Management Institute
KP	Kyoto Protocol
LULUCF	Land Use, Land Use Change and Forestry
MODIS	Moderate Resolution Imaging Spectrometer
NIMA	National Imagery and Mapping Agency (USGS)
PCF	World Bank Prototype Carbon Fund
SBSTA	Subsidiary Body for Scientific and Technological Advice
SRTM	Shuttle Radar Topography Mission
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
USGS	United States Geological Survey
WDPA	World Database of Protected Areas
WHO	World Health Organization

Summary

Climate change and global warming have become familiar notions throughout the world, as the profound impact that human activities have made on global biogeochemical cycles is increasingly recognized. The global carbon cycle has received much international attention as it has become increasingly obvious that increased levels of CO_2 in the atmosphere are causing changes in our climate at an alarming rate. The Kyoto Protocol is an international effort aimed at mitigating climate change through the reduction of greenhouse gas emissions into the atmosphere. Within the Kyoto Protocol, the Clean Development Mechanism (CDM) is an instrument which is 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 reforestation and afforestation (CDM-AR) projects.

In this report, we articulate the 'hidden' water dimensions of international efforts to mitigate climate change through multilateral treaties through a global analysis of land suitability and water use impacts of CDM-AR carbon 'sink' projects. Large amounts of land were identified globally as biophysically suitable and meeting the CDM-AR eligibility criteria. The eco-sociologic characteristics of these suitable areas were examined, with results showing that much of this land is under rain-fed and/or subsistence agriculture or savannah land. Large amounts of suitable land exhibited relatively low population densities. Generally, most of this land is below 1,000 meters (m) in elevation and of moderate productivity.

If converted to forest, large areas deemed suitable for CDM-AR would exhibit increases in actual evapotranspiration and/or decreases in runoff, i.e., a 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. However, major direct impacts of CDM-AR at the global and regional scales on water resources and food security are ascertained as unlikely, primarily due to the UNFCCC mandated cap on CDM-AR at one percent per annum of total emission obligations. However, significant changes in CDM-AR rules affecting the number of projects or amount of land that could eventually be under CDM-AR, should take into account these potential impacts on the hydrological cycle, and related food security issues. At the local and project level scale, impacts on water use was substantial. It was evident that CDM-AR projects can benefit from identifying locally optimal locations for tree plantations that maximize the positive aspects of increased 'green water' vapor flows and reduced runoff.

This report highlights the potentially significant impacts on the hydrologic cycle and the importance of considering secondary effects, particularly with regard to water, resulting from the widespread adoption of global climate change mitigation measures. It is recommended that the implicit hydrologic dimensions of climate change mitigation should be more formally articulated within the international environmental conventions, and recognized within future UNFCCC negotiations on the CDM-AR provisions.

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Introduction

Human activities have profoundly affected global biogeochemical cycles and it is widely predicted that human induced climate change will significantly affect the biosphere of our planet. The global carbon cycle has received the most attention in recent years as it has become evident that increased levels of CO_2 in the atmosphere are causing changes in our climate at an alarming and accelerating rate (IPCC 1996; IPCC 2001). While many factors play into the complex equation of the impact of greenhouse gas (GHG) emissions on the concentration of gases in the atmosphere, such as buffering by the world's oceans, there are two essential mitigation strategies available: emission reductions, or fixation of atmospheric CO_2 into so-called sinks, mainly biomass and ecosystems through photosynthesis. When this carbon fixation is semi-permanent, such as in forests, or recalcitrant soil organic matter, it is termed 'carbon sequestration'. Partial solutions to increased atmospheric CO_2 concentrations can therefore be found in sequestering carbon in terrestrial ecosystems (IPCC 2000). Forests and trees are important in this regard because they store large quantities of carbon in vegetation and soils. Forests are both sources of atmospheric CO_2, when disturbed by natural or human causes, and sinks when vegetation and soil carbon accumulate after afforestation or natural revegetation.

International efforts have mobilized to address climate change and other global environmental problems with global treaties and other legally mandated frameworks to minimize and mitigate impacts, including such agreements as the United Nations Framework Convention on Climate Change (UNFCCC), the Convention on Climate Change, with the Kyoto Protocol (KP), the Convention on Biological Diversity, the Convention to Combat Desertification, and more. Each sets up institutions and mitigation measures that address global change issues and processes, and create 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, and can have both intended and unintended effects on carbon and other biogeochemical processes, but also on hydrologic cycles. In this report we articulate the implicit hydrologic dimensions of international efforts to mitigate climate change, specifically investigating potential impacts of the Clean Development Mechanism - Afforestation/Reforestation (CDM-AR) provisions of the KP. The CDM-AR allows for carbon sequestration offsets of emission reduction obligations for the developed countries, through the purchase of 'carbon credits' from afforestation/reforestation projects in developing countries. These activities are generally referred to as 'sink' projects. This study delineates the potentially suitable areas for CDM-AR projects globally, describes the socio-ecological characteristics of these suitable lands, and estimates the impacts of CDM-AR on global, regional and local water cycles.

Background

In 1992, the *United Nations Framework Convention on Climate Change* (UNFCCC) was the first international convention to recognize the problem of climate change. It set out the objective of stabilizing GHG concentrations in the atmosphere to prevent dangerous interference with climate. The risks of climate change to food production and the importance of adaptation were particularly highlighted. The UNFCCC primarily encouraged developed countries to stabilize emissions. In 1997, specific legally-binding targets and timetables for cutting emissions were developed and adopted as part of the KP to the Convention (UNFCCC). The KP allows for various mechanisms to achieve these targets, including the Clean Development Mechanism (CDM). CDM projects provide credit for financing emissions-reducing or emissions-avoiding projects in developing countries. It is hoped that the CDM will be an important new avenue through which governments and private corporations can promote sustainable development and transfer of clean technologies. Land use, land use change, and forestry (LULUCF) activities were included in the KP CDM instrument, recognizing the role of land use, and particularly forests, in regulating carbon cycles (Brown et al. 2002). The ability of forests (and land) to be both a source and sink for carbon allow for manipulation of these processes through forest management and other human activities, at a significant scale, i.e., meaningful in terms of climate change mitigation. However, the inclusion of these so-called ‘sink projects’ and the rules governing eligibility of LULUCF carbon offset credits were, and are, controversial, producing ample debate during the various rounds of negotiations (Kolshus 2001; Kolshus et al. 2001; Forner and Jotzo 2002; Jung 2003). Concerns center on whether CDM is a (too) cheap or easy way for Annex I Countries to avoid actual emission reductions, and that CDM-AR has a higher risk of leakage and unsustainable practice (Greenpeace 2003). Although the KP has only recently entered into force, and the first commitment period is from 2007-2012, much effort has already gone into developing CDM and CDM-AR projects. 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, more specifically for CDM-AR. In addition, there have been various capacity building activities for recipient countries and substantial private sector activity has developed (Huq 2002).

Clean Development Mechanism

One of the main purposes 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. The CDM is intended to provide a market vehicle through which developed countries with high rates of CO_2 emissions (referred to as Annex I Countries) can offset part of their emissions by purchasing carbon credits in developing countries. Bioenergy production is one CDM strategy in which biomass is grown (CO_2 is fixed) and then used for energy production (CO_2 is released again), thus they substitute 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, that is, currently through afforestation and reforestation (CDM-AR) projects. There is considerable optimism in developing countries and the development community that the potential investments represented by CDM sink projects can be a boon for rural development and environmental protection, if properly directed and monitored. Many countries are already heavily 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 plantation
- 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, around and between existing forest fragments through planting and natural regeneration)
- 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/ deforestation is accepted as eligible, as agreed at COP 7 in Marrakech (UNFCCC 2002a; UNFCCC 2002b).

Sink projects continue to be controversial and developing the rules governing their inclusion into global climate change treaties has been long and arduous. Compared to the CDM technology transfer activities, CDM-AR projects involve a fundamental change in land use. Technology transfer makes an activity more efficient and/or less dependent on non-renewable energy sources. Reforestation and/or afforestation is fundamentally different, implying the cessation of one land use activity and its substitution with another, thus presenting several unique challenges in both carbon accounting and implementation. To make CDM-AR a positive development vehicle, rules were agreed upon and methodologies are being developed that attempt to reduce the risk of 'perverse incentives' that may result in social or environmental harm, and that adequately verify carbon sequestration, local environmental and sustainable development benefits, and secure carbon credits.

Environmental and Social Issues of CDM-AR

Reforestation and/or afforestation represents a fundamental change in the local ecological landscape and can have unintended consequences or contribute to ecosystem degradation. Loss of biodiversity, or other ecosystem services, can result from establishment of extensive fast growing plantation forests that are economically favored in terms of low costs per return in fixed carbon. Additionally, some activities may increase erosion, through disturbances caused by planting, establishment, and building of access roads.

CDM-AR projects can also have negative impacts on rural societies and local economies where people are dependent upon project area resources. For example, indigenous land claims may be infringed when treaties and agreements are signed at the national level without taking into account local institutions or how benefits might be equitably shared. Changes in local economic activity can also affect key factors in sustainable development such as gender workloads (for example, increasing women's workload by forcing them to go further for firewood and water). Projects must engage local population in finding alternative sources of livelihood, if these are affected, or provide adequate compensation (Smith and Scherr 2002). Effective carbon sink projects must be integrated into local sustainable development, and involve far more than simply planting trees, including concern for off-site impacts on resources.

In response to these concerns and other potential negative aspects associated with CDM-AR, several organizations have highlighted important social justice and environmental conservation aspects that are to be evaluated early in project cycles (see http://www.climate-standards.org). One such environmental and social issue that has thus far been generally overlooked is the water use dimension of carbon sequestration projects. Most terrestrial carbon fixation is the result of plant growth and photosynthesis. This process requires water from the ecosystem, which, if an increase in carbon stock is achieved, almost certainly means an increase in vapor flows, actual evapotranspiration (*AET*), and local in situ water use.

Water Supply and Carbon Sequestration

Water supply and scarcity has received increasing attention over the last decade, primarily driven by alarming WHO figures (2006) that 1.1 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. 2006). Numerous projections with regard to water supply and scarcity focus on the rising 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 percent by 2025 to meet growing food needs (IWMI 2000; FAO 2001b, 2003a, 2003b; Shiklomanov 1998). Many estimates agree that up to two-thirds of the world population will be affected by water scarcity over the next several decades (Shiklomanov 1991; Raskin et al. 1997; Seckler et al. 1998; Alcamo et al. 1997, 2000; Vorosmarty et al. 2000; Wallace 2000; Wallace and Gregory 2002).

Increasing demands for water to meet direct human needs will be felt most strongly where aquatic and terrestrial ecosystems alike already suffer from diversions of water for food production. The conflict between water diversions to agriculture and maintaining aquatic ecosystems has received the most attention. Environmental flow requirements (Smakhtin et al. 2004) are increasingly being taken into account to manage water allocations, to allow for the perpetuation of natural areas, wildlife and endangered species habitats, and environmentally sensitive wetlands. Links are now also being made between water for agricultural food production and water for terrestrial ecosystem services (Rockstrom et al. 1999).

Other ecosystem service demands for water, e.g., increased on-site vapor flows associated global climate change mitigation, are as yet rarely considered in these discussions. This is partly due to an under-appreciation that carbon fixation through biomass production will require consumption of water that will then not be available for other uses. A historical hydrological bias in water accounting considered only surface runoff and groundwater as available water supply and viewed terrestrial ecosystems and forests as water-provisioning rather than water consumptive (Falkenmark and Lannerstad 2004). The ongoing 'debate' on 'forests and water' has lately been the subject of much interest and research (CIFOR and FAO 2005), most notably through ecosystem evapotranspiration studies (L'vovich and White 1990; Gordon et al. 2005), the introduction of the concepts of green and blue water management in agriculture by Falkenmark (1995), Rockstrom et al. (1999), and in the forestry sector by Calder (2000). Only recently have a few studies highlighted the implications of global climate change mitigation strategies on water use (Aylward et al. 1998; Calder 2000; Berndes 2002; Heuvelmans et al. 2005). An 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 'green water' vapor flow demand for water into sharp focus.

Forests and Water

It is generally accepted that tree removal by logging, forest fire, or wind damage increases runoff (Bosch and Hewlett 1982). Jackson et al. (2005) found that plantations decreased stream flow by 227 millimeters (mm) per year globally (52 percent), with 13 percent of streams drying completely for at least one year. The magnitude of this water decrease is proportional to the percentage of vegetation cover and is due to an increase in AET, an increase in the net additions to evaporation from interception losses, and an increase in the root exploring zone from which water is extracted under trees (Dingman 1993). A review of catchment experiments (Bosch and Hewlett 1982) found that pine and eucalypt plantations cause a 40 mm decrease in runoff for any 10 percent increase of forest cover with respect to grassland. The equivalent response of deciduous hardwood and shrubs is 25 and 10 mm decrease in runoff, respectively. Transpiration from trees can be higher than from shorter vegetation because tree root systems exploit deep soil water (Maidment 1992) available during prolonged dry seasons (IPCC 2000).

Recent references (Gedney et al. 2006; Matthews 2006) support the thesis that afforestation is not to be necessarily looked at as a burden for the global hydrological cycle. On-site hydrological effects of afforestation are mainly positive (reduced runoff and erosion, improved microclimate and increased control over nutrient fluxes); the off-site effects may be mainly negative (lower base flow), but in many cases these off-site effects of increased in situ vapor flows may be beneficial for downstream users. Gedney et al. 2006 speculate that increases over the last several decades in total discharge of the world's river systems is a consequence of increased CO_2 in the atmosphere, which makes plants more water efficient, although deforestation may have played an important part in this phenomena.

Research Objectives

In this research report, we analyzed land and water use implications of CDM-AR at two scales, global and local. Land suitability for CDM-AR was modeled, as per the existing rules of the first commitment period, and a simple water balance approach is used to estimate impacts on hydrological cycles resulting from a change to forestry activities. In addition, socio-ecological characteristics of these suitable areas are described, including the land use types that currently exist on these lands, and their population and ecosystem characteristics. A GIS spatial modeling environment is used to delineate biophysical conditions, identify suitable areas for CDM-AR, and predict hydrologic changes with conversion of suitable lands to afforestation/reforestation activities.

Specific Objectives:

1. To delineate areas suitable for CDM-AR, globally.
2. To characterize suitable areas in both biophysical and socio-ecological terms.
3. To estimate potential impacts of adoption of CDM-AR on global to regional hydrologic cycles.
4. To estimate potential impacts of adoption of CDM-AR on local hydrologic cycles based on four in-depth case studies.

Methods

The suitability of CDM-AR projects, as per the current proposed guidelines for their application in developing countries (i.e., Non-Annex I Countries), is constrained by the current UNFCCC guidelines for CDM-AR projects within the first commitment period (2008-2012), 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:

1. 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).
2. Suitability of the biophysical environment to support relatively robust biomass production (i.e., fixation of GHG) to make the projects viable and economically feasible.

Land Suitability Analysis

A spatial modeling procedure was developed and implemented in ArcGIS (ESRI Inc.) using ArcAML programming language, and used to identify areas meeting a range of suitability criteria as outlined below. All areas that are not likely to be suitable for these projects, due to the following environmental and social factors, have been excluded a priori from our analysis:

- Arid/semi-arid areas with high Aridity Index (AI < 0.65)
- High elevation areas, above 3,500 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

In addition, areas that are ineligible for CDM-AR due to UNFCCC rules have been excluded from the analysis:

- Currently forested areas. A threshold of 30 percent canopy cover was used as the forest definition, as per results of an earlier analysis of forest definitions on areas available at a national scale (Verchot et al. 2006).

Recently deforested areas, in this case, areas that are identified as forest in the USGS 1993 land use classification but currently exhibit a crown cover of less than 30 percent, as per guidelines that exclude recently deforested areas from being eligible for CDM-AR, were delineated and quantified.

The results of the land suitability analysis are mapped and tabulated on a national, regional (sub-continental), and global basis. Results of area estimates are articulated by:

- Land Use Types
- Population Density
- Elevation Zone
- Aridity Index
- Net Primary Productivity Class (NPP)

Environmental and other global geospatial datasets used within the global analysis include:

(Spatial resolution: 500 m – 1 kilometer (km) / 15 - 30 arc-seconds)

- 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 on 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 2001a)
- Gridded Population of the World (2000) (GPWv3 - 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)

All datasets used for the analyses have been re-projected and processed in two coordinate systems, sinusoidal and geographic. The geographic coordinate system preserves landform shapes with a perspective that is generally easily recognizable to human perception and is therefore used for map presentation. The dataset in sinusoidal projection was used to calculate zonal statistics and carry out areal computations, because it represents area extent accurately for all pixels across latitudes (equal-area projection) while the geographic does not. The cell size for analyses in geographic projection is equal to 0.004497 degrees (15 arc-seconds, ~ 1 km at equator and 500 m at 60 degrees latitude), while the cell size for analyses in sinusoidal projection is 500 m.

Forest Definition, Canopy Cover Percentage, and Recently Deforested Areas

CDM-AR projects are only eligible and allowed in currently non-forested areas. ‘Forests’ are individually defined by each Non-Annex I Country as areas within a range of 10-30 percent canopy cover, along with a minimum size and height criteria (Verchot et al. 2006), based upon the ‘Marrakech Accords’ agreed to at COP 7. Reforestation projects are allowed only in sites that were not forested on December 31, 1989 (afforestation generally refers to sites that have not had forest cover for more than 50 years). The MODIS Vegetation Continuous Fields dataset (Hansen et al. 2003), a global dataset of tree canopy cover extracted from multi-temporal sequences of MODIS data (year 2001; resolution 15 arc-seconds) was used in this study to determine currently forested areas. This was compared with the Land Characteristics Database (USGS 1993) to ascertain recently deforested areas.

Elevation limits for CDM projects

Areas above and approaching timberline were not considered suitable and were estimated as areas with average temperature in the growing season below 6.5^{o} C, according to Korner and Paulsen (2004) and using length of the growing season calculations based on the WorldClim dataset (Hijmans et al. 2004). Although treeline can surpass 4,000 meters in certain parts of the world, CDM projects have been considered unrealistic at elevations above 3,500 meters. Thus, all land above 3,500 meters, (estimated based on the SRTM DEM) was excluded.

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 +- 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-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 2000-2004 period have been aggregated into one average annual NPP dataset and used to analyze the current productivity of land deemed suitable for CDM-AR.

Water Balance Model

A spatially distributed Thornthwaite-Mather water balance approach (Thornthwaite 1948; Thornthwaite and Mather 1955) was used to examine hydrological differences in AET, soil water content and runoff. This model uses the average spatially distributed values of monthly precipitation and monthly potential evapotranspiration (*PET*), land use classes, soil depth and soil water holding capacity, and returns monthly spatially-distributed raster data representing actual evapotranspiration (*AET*), surface runoff (*R*) and soil water content (*SWC*). All the results are computed on a monthly basis throughout a year for existing land use and proposed CDM-AR scenarios, and the results are aggregated into yearly figures.

A soil water balance budget is computed as height of water in mm for each month (*m*), as:

$$\Delta SWC_m = EPrec_m - AET_m - R_m \quad \text{mm/month} \qquad [1]$$

where: ΔSWC_m is the change in soil water content, $EPrec_m$ is the effective precipitation, AET_m is the actual evapotranspiration, and R_m is the runoff component, which includes both surface runoff and subsurface drainage. *SWC* can never exceed a maximum value, SWC_{max}, which is the total *SWC* available for evapotranspiration (*ET).*

Therefore, the *SWC* at the end of the month, SWC_m^f is equal to:

$$SWC_m^f = \begin{cases} SWC_m^b + EPrec_m - AET_m - R_m & \text{if } SWC_m^f > SWC_{max} \\ SWC_{max} & \text{if } SWC_m^f \leq SWC_{max} \end{cases} \qquad [2]$$

Where: SWC_m^b is the soil water content at the beginning of the month. The *SWC* at the end of the month, SWC_m^f, is set as the *SWC* at the beginning of the following month, SWC_{m+1}^b All the water exceeding SWC_{max} is accounted as runoff:

$$R_m = \begin{cases} SWC_m^b + EPrec_m - AET_m - SWC_{max} & \text{if } SWC_m^b + EPrec_m - AET_m > SWC_{max} \\ 0 & \text{if } SWC_m^b + EPrec_m - AET_m \leq SWC_{max} \end{cases} \qquad [3]$$

Monthly Potential Evapotranspiration (PET)

Potential evapotranspiration (*PET*) was estimated on a global scale to calculate the Aridity Index (*AI*) for the land suitability analysis and later used to explore hydrologic impact. *PET* is a measure of the ability of the atmosphere to remove water through *ET* processes. The FAO introduced a definition of *PET* as the *ET* of a reference crop in optimal conditions having the following characteristics: well watered grass with an assumed height of 12 centimeters (cm), a fixed surface resistance of 70 seconds per meter (s/m) and an albedo of 0.23 (Allen et al. 1998). Five different methods of calculating *PET* (table 1) were tested to verify which equation performed the best for the objectives of this analysis: Thornthwaite (Thornthwaite 1948), Thornthwaite modified by Holland (Holland 1978), Hargreaves (Hargreaves et al. 1985), Hargreaves modified by Droogers (Droogers and Allen 2002), and the FAO Global Penman-Monteith Dataset (Allen et al. 1998). Values of *PET* estimated using each of the above five methods were compared to Penman-Monteith *PET* values estimated at climate stations in South America and Africa (n = 2288). Based on the results of the comparative validation for South America (figure 1) and Africa (figure 2), the Hargreaves model was chosen to

TABLE 1.
Five different methods of calculating *PET* were tested to verify which performed the best for the objectives of this analysis: Thornthwaite (Thornthwaite 1948), Thornthwaite modified by Holland (Holland 1978), Hargreaves (Hargreaves et al. 1985), Hargreaves modified by Droogers (Droogers and Allen 2002), and the FAO Global Penman-Monteith Dataset (Allen et al. 1998). Results are given as the mean difference (Diff) between observed and predicted estimates, and their standard deviations (*SD*).

Comparison of 5 Methods for Estimating PET:

		Mean Difference (mm) and Standard Deviation (mm) between Observed and Predicted Values				
		Holland (Thornthwaite)	Thornthwaite	Hargreaves	Modified Hargreaves	Penman-Montieth FAO
Region	Month	Diff (*SD*)	Diff (*SD*)	Diff (*SD*)	Diff (*SD*)	Diff (*SD*)
Africa	Jan	71.8 *(40.2)*	41.6 *(33.3)*	22.3 *(16.1)*	24.8 *(20.1)*	11.1 *(12.6)*
	July	84.4 *(41.7)*	32.1 *(23.7)*	20.0 *(19.3)*	21.1 *(19.3)*	12.7 *(16.0)*
South America	Jan	69.9 *(43.6)*	50.5 *(32.9)*	38.2 *(19.2)*	41.6 *(26.0)*	34.9 (26.7)
	July	67.3 *(35.9)*	37.2 *(24.7)*	27.2 *(14.0)*	30.4 *(20.1)*	24.3 *(15.1)*
Resolution		1 km	1 km	1 km	1 km	20 km
Data Requirements		Average Temperature	Average Temperature	Average Temperature Average Extraterrestrial Radiation Average Temperature Range	Average Temperature Average Extraterrestrial Radiation Average Temperature Range Average Precipitation	Large Collection of Climate Data

model *PET* globally for this study. This method performed almost as well as the FAO Penman-Monteith, but required less parameterization, and with significantly reduced sensitivity to error in climatic inputs (Hargreaves and Allen 2003). This allowed for its application at a finer resolution (at 1 km; resolution of the FAO Penman-Montieth dataset is 20 km). Hargreaves (1994) uses mean monthly temperature (T*mean*), mean monthly temperature range (*TD*) and extraterrestrial radiation (*RA*, radiation on top of atmosphere) to calculate *PET*, as shown below:

$$PET = 0.0023 \cdot RA \cdot (Tmean + 17.8) \cdot TD^{0.5} \quad \text{(mm/d)} \qquad [4]$$

Aridity Index

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

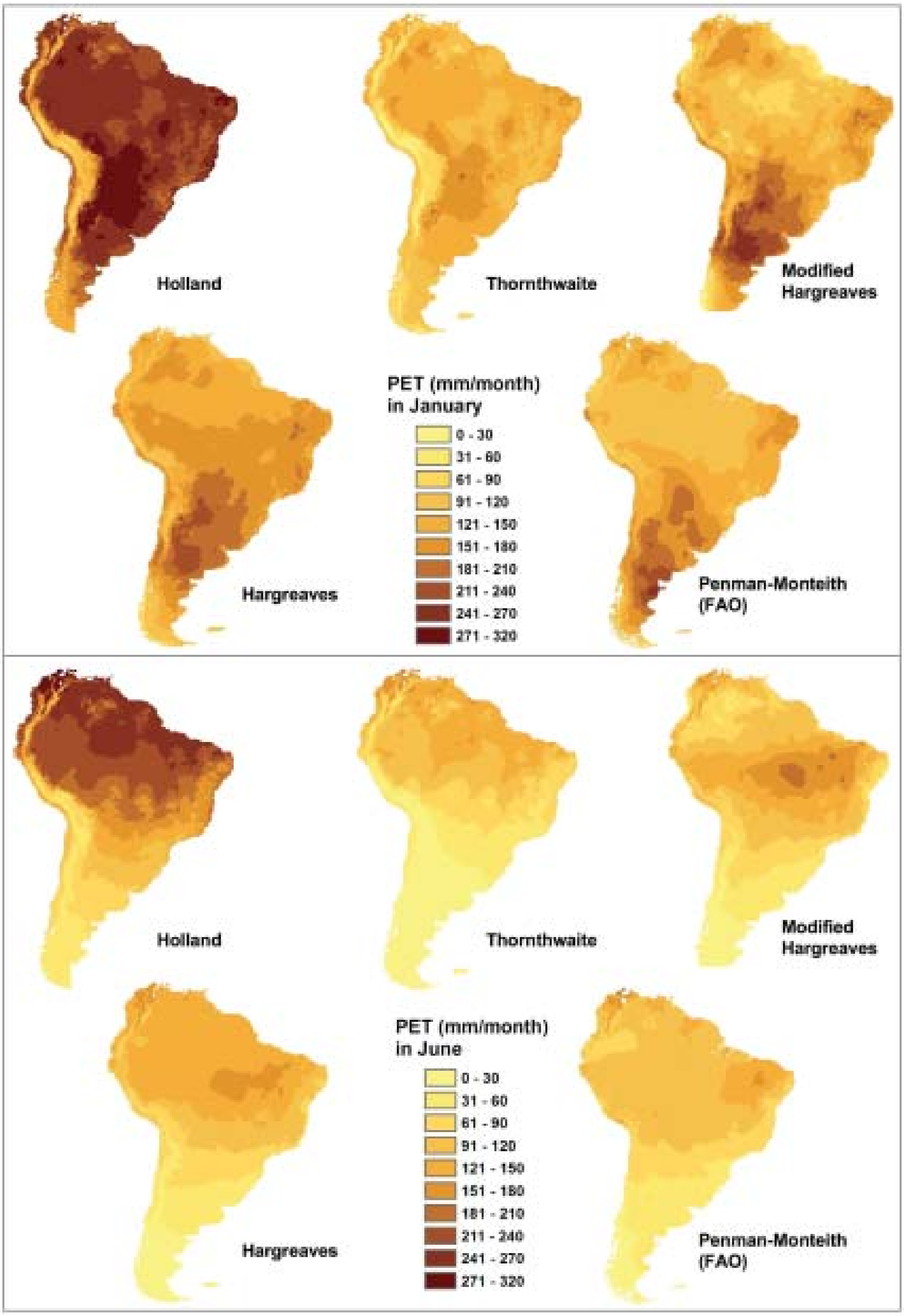
$$\text{Aridity Index } (AI) = MAP \,/\, MAE \qquad [5]$$

where:

MAP = mean annual precipitation
MAE = mean annual evapotranspiration.

Monthly values for precipitation, and minimum, maximum, and mean temperature were obtained from the WORLDClim dataset (Hijmans et al. 2004) for years 1960-1990, at a

FIGURE 1.
Comparison of five methods of calculating *PET* for South America during two seasons.



resolution of 30 arc-seconds, or ~1 km at equator.

The global *AI* dataset produced in the analysis 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 zones for CDM-AR were ascertained as *AI* > 0.65. This lower threshold for suitability represents the moisture range of the semi-arid zones (UNEP 1997), which can support rain-fed agriculture with more or less sustained levels of production.

Actual Evapotranspiration and Green Water Vapor Flows

Actual evapotranspiration (*AET*) is the quantity of water that is removed from the soil due to evaporation and transpiration processes (Maidment 1992). *AET* is dependent on vegetation characteristics, quantity of water available in the soil and soil hydrological properties (mainly soil water retention curves) (Allen et al. 1998):

$$AET_m = K_{veg} * K_{soil} * PET_m \quad \text{mm/month} \qquad [6]$$

where:

K_{soil} = reduction factor dependent on volumetric soil moisture content (0-1)

K_{veg} = vegetation coefficient dependent on vegetation characteristics (0.3-1.3)

The vegetation coefficient (K_{veg}) is used to 'correct' the reference *PET* for different crops or vegetation types. K_{veg} values for the various land use types were modeled by combining K_{veg} coefficients for vegetation types taken from the literature, and their estimated occurrence within each land use type. K_{veg} values are available from literature for agronomic crops (Allen et al. 1998) and for other vegetation types from various sources (Allen et al. 1998; Costello and Jones 2000; U. S. Bureau of Reclamation 2005).

The maximum amount of soil water available for *ET* processes within the plant rooting depth zone, here defined as SWC_{max}, is equal to the *SWC* at field capacity (SWC_{fc}) minus the *SWC* at wilting point (SWC_{wp}) times the rooting depth.

$$SWC_{max} = RD * (SWC_{fc} – SWC_{wp}) \qquad [7]$$

where:

SWC_{max} = maximum soil water content available for ET (mm)
RD = rooting depth (mm)
SWC_{wp} = soil water content at wilting point (mm/mm)
SWC_{fc} = soil water content at field capacity (mm/mm)

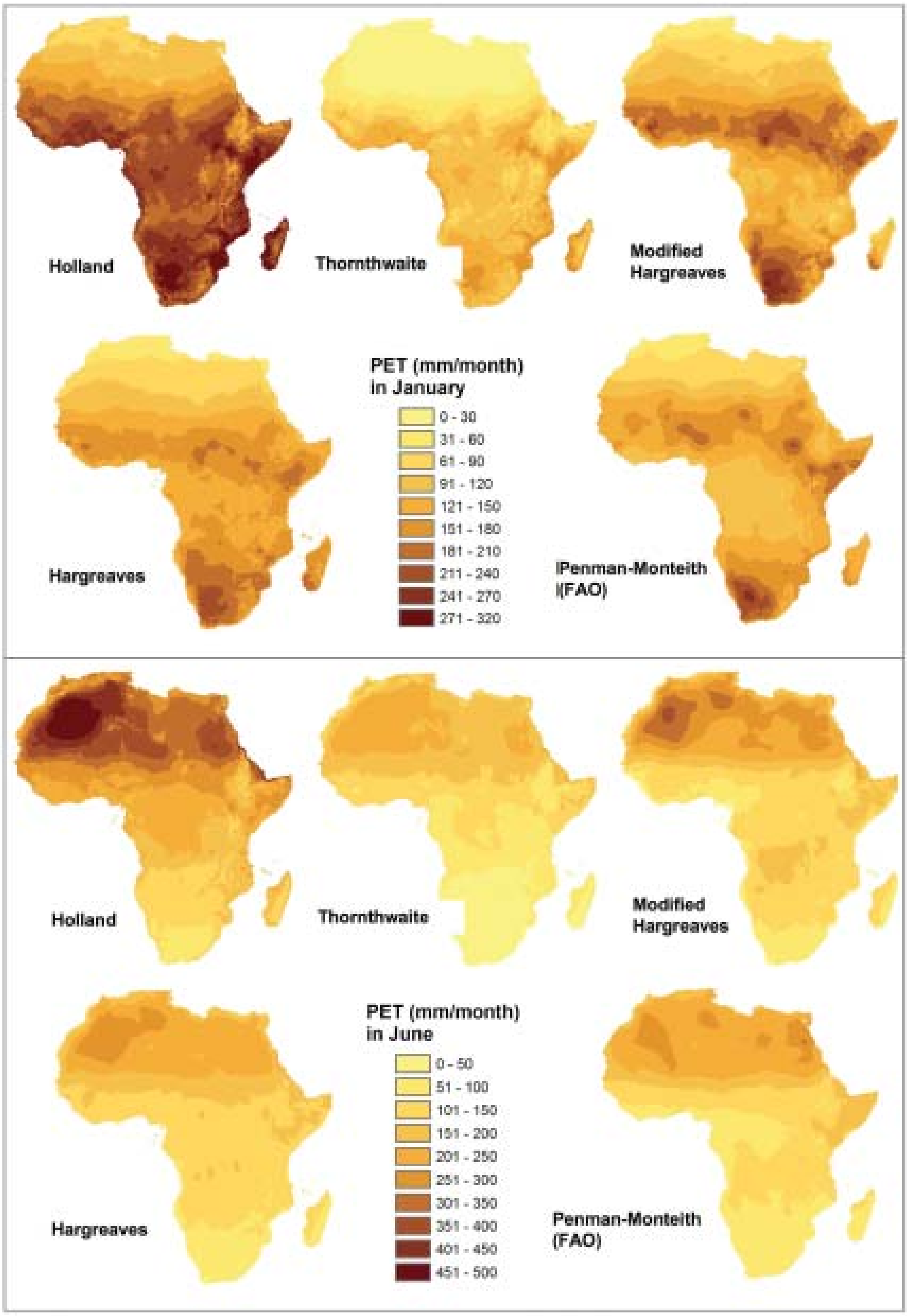
Soil water content at field capacity and wilting point are available from literature for the various soil texture typologies (Jensen et al. 1990). Rooting depth values for the various land use types were modeled by combining rooting depth of specific vegetation types under irrigated and non-water stress conditions, and their estimated occurrence within those land use types. Rooting depth of vegetation is likely to be deeper under water stressed conditions, as water is stored more in depth in the soil during dry seasons. Rooting depths values for vegetation types under irrigated and non-water stress conditions are available from the literature (Allen et al. 1998). A global dataset of ecosystem rooting depth (Schenk and Jackson 2002) was used to scale rooting depth of the various vegetation types to more realistic water stressed conditions.

The soil stress coefficient (K_{soil}) represents the *ET* reduction factor resulting from the limit imposed by the absolute volumetric soil moisture content. The model uses a simple linear soil moisture stress function that is considered appropriate for monthly computation (Dyck 1983):

$$K_{soil_m} = SWC_m / SWC_{max} \qquad [8]$$

SWC_m = soil water content averaged over the month

FIGURE 2.
Comparison of five methods of calculating *PET* for Africa during two seasons.



Effective Precipitation

Rain interception is the process by which precipitation is intercepted by the vegetation canopy (canopy interception losses) and litter (litter interception losses), where it is subject to evaporation. Interception has an important role in the water budget, as it reduces the amount of precipitation available for soil moisture. Additionally, it protects the soil surface from erosion by reducing the rainfall energy (Tate 1996). The losses due to interception depend on vegetation type, vegetation cover and the intensity, duration, frequency and form of precipitation (Dingman 1993). Observations derived from several experiments demonstrate that vegetation interception is a purely mechanic function of the storage space of vegetation structure (Wilm 1957). Forests with dense crowns and large leaf areas are expected to have higher interception losses (IPCC 2000). Interception losses are on average greater for evergreen forest compared to seasonally leaf-shedding (Schulze 1982; Tate 1996) and for fast-growing trees compared to slow-growing trees (IPCC 2000). Thin or sparse vegetation shows low values of interception (Wilm 1957). Interception values for the various land use types were modeled by combining interception values from the literature for the various vegetation types (Hamilton and Rowe 1949; Young et al. 1984; Thurow et al. 1987; Farrington and Bartle 1991; Calder 1992; Le Maitre et al. 1999; Schroth et al. 1999), and the estimated occurrence of that specific vegetation within a land use type.

Effective precipitation (*EPrec*), that part of precipitation that adds moisture to the soil, is calculated as the gross precipitation (*GPrec*) minus the precipitation intercepted by canopy cover and litter (*Int*). The quantity of rain intercepted is proportional to the interception coefficient K_{int}, specific for different types of land use types, calculated as a fraction of *GPrec*. There is a wide availability of such coefficients from literature for different vegetation types (Tate 1996).

For each month $EPrec_m$ is calculated as:

$$EPrec_m = GPrec - Int \qquad [9]$$

where: *Int* is equal to:

$$Int = (GPrec * K_{int}) \qquad [10]$$

Therefore:

$$EPrec_m = GPrec - (GPrec * K_{int}) = GPrec * (1 - K_{int}) \qquad [11]$$

We combine the AET and *Int* components of the model to quantify ‘green water’ vapor flows, i.e., that portion of precipitation that evaporates into the atmosphere, and is not available as runoff (or ‘blue water’).

Local Water Use Impact

In order to investigate local and project level water use, a similar water balance approach was applied in four case study sites identified for CDM-AR (Zomer et al. 2004). These sites represent a range of biophysical conditions and project scenarios, with two sites in Ecuador and two in Bolivia (table 2):

TABLE 2.
Socio-ecological characteristics and project scenarios for the four case study sites.

Project Site	Ecological Zone	Elev (m)	Precip (mm/yr)	Temp (°C)	Pop	Project Type
Tunari NP, Bolivia	Sierra	2,800-5,100	900	7-18	22,000	Ecological Restoration
Chapare, Bolivia	Amazon	200-1,000	3,000	23-26	9,000	Small Farm Agroforestry
Guamote, Ecuador	Sierra	2,900-3,700	700	7-12	5,300	Community Plantations
Coastal Ecuador	Tropical Coastal	0-500	1,300	23-25	8,900	Mixed Species Agroforestry

Note: Elev=Elevation; Precip=Precipitation; Temp=Temperature; Pop=Population.

Case Studies:

1. Tunari National Park, Bolivia - Sierras, ecological restoration, native species
2. Chapare, Bolivia - Amazon, small farmers' agroforestry
3. Guamote, Ecuador - Sierras, community based plantation scheme
4. Coastal, Ecuador - Tropical Coastal Zone, mixed/native species agroforestry

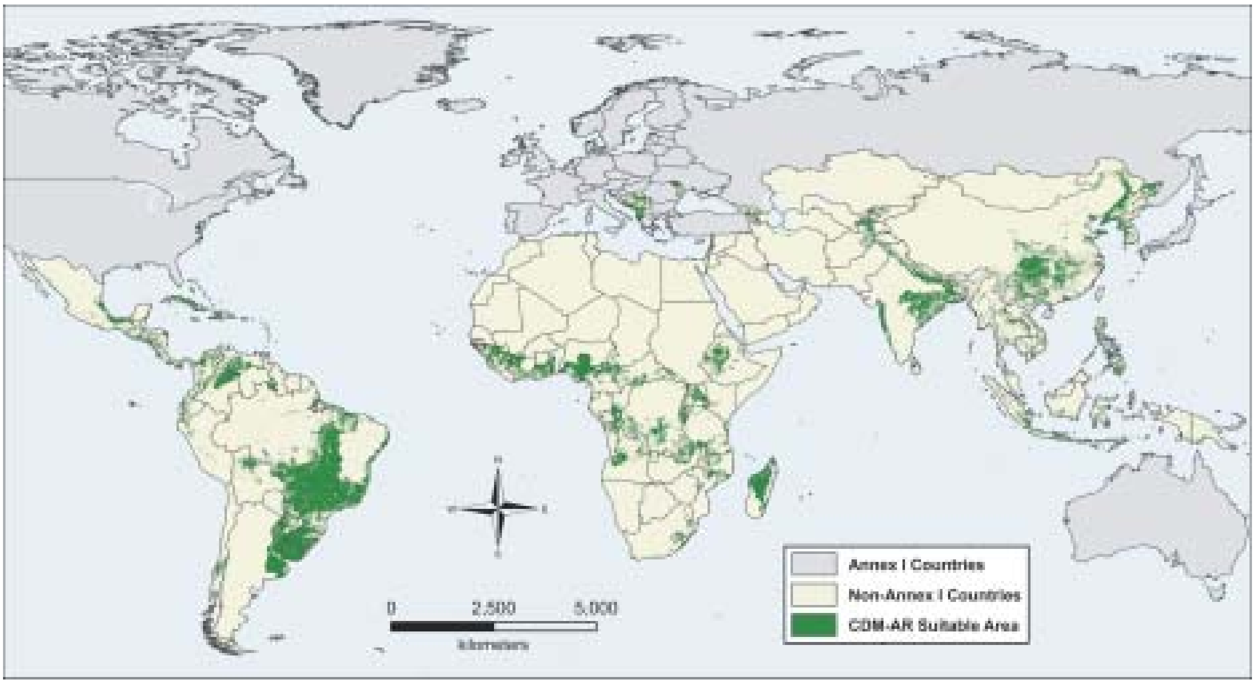
Changes in water cycles were modeled as a consequence of land use change to a specific proposed CDM-AR scenario, at a resolution of 30 m for the four case study sites, using both global and locally available data, and comparing the proposed CDM-AR project scenario for the site with the current land use. Tree canopy cover, current and historical, was estimated from Landsat TM imagery, and elevation was derived from SRTM 90 m DEM data (available from CGIAR-CSI: http://srtm.cgiar.csi.org). Growth characteristics for specific species were obtained from literature and expert knowledge, where available (Zomer et al. 2006).

Results and Discussion

Lands suitable for CDM-AR

CDM-AR projects are subject to a complex set of eligibility guidelines as defined within the UNFCCC in order to be certified to provide carbon emission reduction credits under the CDM. Our global spatial analysis identified all land surface areas that meet a minimal set of eligibility criteria, both statutory and biophysical (figure 3). Results were calculated for the entire world, and altogether, globally more than 760 million hectares (Mha) of land were found to be suitable, representing just over nine percent of total land surface area within the Non-Annex I (developing) Countries. Global totals in this paper are reported as the sum of five regions, which cover most of the developing (i.e., Non-Annex I) countries with significant CDM-AR potential, with the exception of some areas in Central America. Within these five regions, 725 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 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 slowed tropical deforestation, 217 Mha for regeneration of tropical forests, and 345 Mha for plantations and agroforestry. However, Sathaye and Ravindranath (1998) suggest that 300 Mha may be available for mitigation in ten 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 percent of all the suitable areas globally) and Sub-Saharan Africa (27 percent), reflecting the greater landmass of these

FIGURE 3.
Global map of CDM-AR suitable land within Non-Annex I Countries, as delineated by the land suitability analysis. A 30% crown cover density threshold was used to define forest, and protected areas are not included.



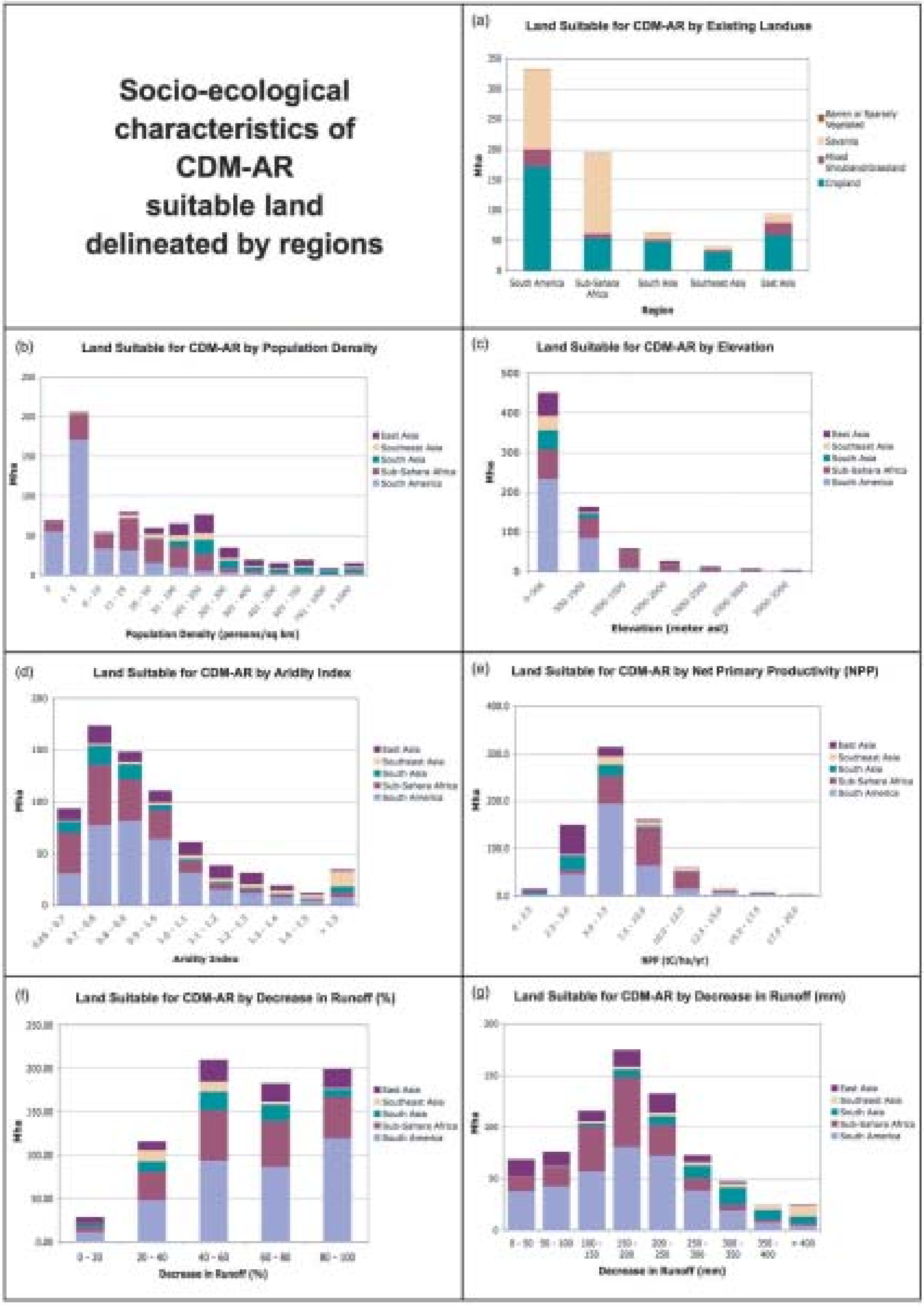
regions, and to a certain extent, lower population densities. Much smaller amounts of land are available in Asia, the three Asian regions together comprising about 200 Mha, compared to more that 330 Mha in South America and almost 200 Mha in Africa. Within the respective regions, the amount of available land ranged from only 8 percent of the total land surface area in Southeast Asia, to more than 19 percent of South America.

As our suitability estimates are based exclusively on biophysical suitability combined with UNFCCC requirements, they naturally 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 set within a national, local and site-specific socio-economic and ecological context. These conditions go beyond the CDM-AR rules, or the biophysical fact that trees grow well on any particular piece of land, to include such factors as land opportunity costs, access to markets, tenure, or national level infrastructure and support. It is estimated that a substantially smaller proportion of this identified area will meet the more specific criteria which are required to make CDM-AR a viable option for landowners, land managers, communities, and/or national planners.

Current land use, population and ecosystem characteristics of CDM eligible lands

To understand the socio-economic and ecological nature and characteristics of the areas identified as suitable, and to better judge the likelihood of CDM-AR projects being realized there, eligible lands identified by the global analysis were characterized by existing land use class, population density, elevation zone, aridity index, and productivity classes (figure 4). These factors, beyond biophysical suitability, contribute to the likelihood of land being converted to CDM-AR

FIGURE 4.
Socio-ecological characteristics of CDM-AR suitable areas: (a) Existing landuse; (b) Population density (persons/sq km); (c) Elevation (meters asl); d) Aridity Index (*AI*); (e) Net Primary Productivity (NPP) (tC/ha/yr); (f) Percentage decrease in runoff (%) with land use change to CDM-AR; and (g) Decrease in runoff (mm) with land use change to CDM-AR.



because they reflect current land use activities, the number of people who may be dependent on that piece of land, its productivity, and potential opportunity costs of CDM-AR projects.

Land Use. Across the five regions, more than 50 percent of all the eligible area is classified as within an agricultural land use type, constituting more than 364 Mha (figure 4a). This is not surprising, and in line with generally accepted assumptions about availability of CDM-AR suitable land. Since the criteria specify that forested areas are not eligible, and since much deforestation has occurred to make room for agriculture, by elimination, agricultural land is left as likely to be available. While intensive production sites have been excluded from this analysis, it is likely that other agricultural areas are ideal for optimal tree growth, with deeper soils, better climate, adequate moisture, and also meet the CDM-AR criteria, i.e., are not currently forested. However, the probability for much of this area, either currently under commercial production, or in subsistence farming, to actually convert 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).

Both South Asia and Southeast Asia have a very high percentage of the land identified as suitable for CDM-AR classified as under agricultural land use types (76 percent), with much smaller areas of shrubland and savannah (table 3), reflecting the high population densities and pervasive agricultural production found in these regions. Much of the hilly land in South Asia and the Himalayan foothill areas have canopy cover percentages above the threshold for forest, although many of these areas are under various forms of intensive agricultural production.

More than 52 percent (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 Aridity Index was set at a threshold that generally indicates a lack of water stress, these included savannah areas that can be considered as more mesic and fairly productive. Sub-Saharan Africa has a large amount of savannah (132 Mha) classified as suitable (68 percent), where it is likely that substantial pastoralist and other subsistence livelihood activities are present, even in less populated areas. Much of this savanna land, although identified as biophysically suitable for tree growth, has a very low probability of being converted to CDM-AR. These semi-arid lands do have a potential for agroforestry, and may also have other options beside tree plantations for increasing on-site carbon. Restoration of dry forest, for example, addressing losses of these types in the highlands of Ethiopia or Madagascar, although exhibiting very slow growth, can have significant potential for sequestering carbon over

TABLE 3.
CDM-AR suitable land by existing landuse type, by total area (Mha), and percent (%) of the total suitable land, regionally and globally.

	Existing Landuse Type								
	Cropland		Mixed Shrubland/ Grassland		Savanna		Barren/ Sparsely Vegetated		Total
Region	Mha	%	Mha	%	Mha	%	Mha	%	
East Asia	59	*63*	20	*21*	14	*15*	0	*0.1*	93
Sub-Sahara 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*	725

the long term (IPCC 2000). It is likely, however, that slow growing dry forest CDM-AR projects will require a relatively high price for sequestered carbon, and alternative strategies, for example ecotourism, or subsidies, due to their low financial returns, in order to be viable.

Protected areas and national parks were excluded from this analysis. However, it is recognized that some degraded areas now designated as protected offer optimal opportunities for reforestation and CDM-AR. A relevant example is the Mt. Elgon Reforestation Project (FACE 1998), on the slope of Mt. Elgon in eastern Uganda. This National Park was deforested by massive encroachment during the regime of Idi Amin. Subsequently, the government of Uganda reclaimed this area as a national park, and worked with the FACE (Forests Absorbing Carbon Emissions) Foundation of the Netherlands to fund reforestation, based on the carbon sequestration component of the improved ecosystem services provided by the reforestation and ecosystem restoration. The legal commitment to permanency provided by the Uganda Wildlife Authority to the National Park provided an ideal opportunity for carbon sequestration.

Population. Patterns of rural population densities on suitable land vary widely between regions (figure 4b). Population density is considered here as 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 adoption of CDM-AR projects. Globally, more than 50 percent of all identified areas have population densities less than 25 people/square kilometer (sq km), that is, have relatively low densities, with more than 35 percent with densities less than 5 people/sq km (table 4). Areas in South America have the lowest population levels, with 95 percent of all identified areas having less than 100 people/sq km, and almost 70 percent less than 5 persons/sq km. Sub-Sahara Africa has less empty lands, but still has relatively low population densities associated with these identified areas. More than 85 percent of all areas identified in Sub-Sahara Africa have levels less than 100 persons per sq km. In contrast, East Asia has 55 percent of its identified areas with population levels above 100 people/sq km, with 11 percent above 500 people/sq km. Likewise, South Asia has more than 65 percent of identified areas with population levels above 100 persons/sq km, and 24 percent above 500 persons/sq km. Southeast Asia has 65 percent of identified areas with population levels above 100 persons/sq km, and 33 percent with less than 25 persons/sq km. Much of the low population density classes in South America and Sub-Sahara Africa are comprised of savanna, although particularly in South America, substantial areas of very low population density are classified as agricultural land use types. 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. Globally, large areas identified within the savanna land use class extend up to density classes of about 200 persons/sq km, as influenced by the large amounts of these areas found in South America and Sub-Sahara Africa. It seems that except in Asia, displacement of populations, which is often raised as a potential problem for CDM-AR, is not a major concern.

Elevation. Globally, almost 60 percent of available lands are found below 500 m of elevation (table 5), with almost 80 percent below 1000 m. This trend is generally true for all regions, except Sub-Sahara Africa (figure 4c), which has about 40 percent below 500 m, and almost 50 percent between 500 and 1500 m. In general, the notion that one would find most of these projects in mountainous or sloped areas seems to be discounted at the scale of this analysis, as demonstrated by relatively little available land above 1500 m, less than 10 percent globally, with only 20 percent available above 1000 m. However, it is very likely that on hilly, sloped, or mountainous lands, at more local scales, CDM-AR projects may have comparative advantages, especially if other ecosystem services are taken into account.

TABLE 4.
CDM-AR suitable land by population density class given by area (Mha), and as percent (%) of the total CDM-AR suitable land, regionally and globally.

Population Density (persons/sq km)	0-10	25	50	100	200	300	500	>500	Total
Region	**CDM-AR Suitable Land Area (Mha)**								
East Asia	4	4	7	14	23	13	14	14	93
Sub-Sahara Africa	63	40	30	26	21	5	5	4	195
South America	260	31	15	10	5	4	4	5	333
South Asia	1	0	2	7	18	10	9	16	63
Southeast Asia	5	4	5	7	9	3	3	5	41
	CDM-AR Suitable Land Area (Mha)								
Global	332	80	59	65	76	35	35	43	725
Region	**Percent of Total Regional CDM-AR Suitable Land Area (%)**								
East Asia	4	4	8	15	25	14	15	15	
Sub-Sahara Africa	32	21	15	13	11	3	3	2	
South America	78	9	5	3	2	1	1	1	
South Asia	2	1	3	12	29	15	15	25	
Southeast Asia	11	10	13	18	21	8	7	11	
	Percent of Total Regional CDM-AR Suitable Land Area (%)								
Global	46	11	8	9	11	5	5	6	

TABLE 5.
CDM-AR suitable land by elevation class, given by area (Mha), and as percent (%) of the total suitable land, regionally and globally.

	Elevation Class (m)										
	0-500		500-1000		1000-1500		1500-2000		> 2000		Total
Region	(Mha)	(%)	(Mha)	(%)	(Mha)	*(%)*	(Mha)	*(%)*	(Mha)	*(%)*	
South America	234	*70*	85	*25*	9	*3*	2	*0*	4	*1*	333
Sub-Sahara Africa	74	*38*	50	*26*	40	*20*	18	*9*	12	*6*	195
South Asia	49	*77*	11	*18*	1	*2*	1	*2*	1	*2*	63
Southeast Asia	35	*87*	3	*8*	1	*3*	0	*1*	0	*1*	41
East Asia	59	*63*	14	*15*	7	*8*	6	*6*	8	*8*	93
Global	451	*62*	163	*23*	58	*8*	27	*4*	26	*2*	725

Aridity Index. Approximately 30 percent of the initially identified areas had values below the optimal threshold value of 0.65 for the Aridity Index, globally (figure 4d). Sites with values below 0.65 were considered as sub-optimal for tree growth, and/or in some cases may not be suitable for more than mixed shrub and small woody vegetation types. In Africa, 38 percent of initially identified areas were below the optimal Aridity Index (AI) value of 0.65, and large areas in Sub-Saharan Africa, South America (figure 5) and South Asia were identified within semi-arid zones. While natural forests can be found within these zones, these areas are considered as marginally suitable for CDM. They may, however, be utilized for specialized or focused projects, such as restoration of dry forests. We have excluded these areas in our final assessment of total suitable land.

Net Primary Productivity. Results obtained from a spatial analysis of the NASA MODIS MOD-17A3 NPP product show that lands suitable for CDM-AR generally fall into moderately low to moderate productivity categories (figure 4e), indicating that higher productivity lands, mainly intensive and irrigated cropping and forested areas, were eliminated by the analysis, 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 by the Aridity Index criteria, thus giving a generally Gaussian distribution of productivity classes, centered on a moderately productive mean. Globally, 88 percent of all available land had a NPP below 10 tonnes of carbon/per hectare/per year (tC/ha/yr) (table 6). About 75 percent of available land in Africa and Southeast Asia, and

FIGURE 5.
Aridity Index (*AI*) was calculated for the entire globe, with aridity maps for South America and Africa 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.

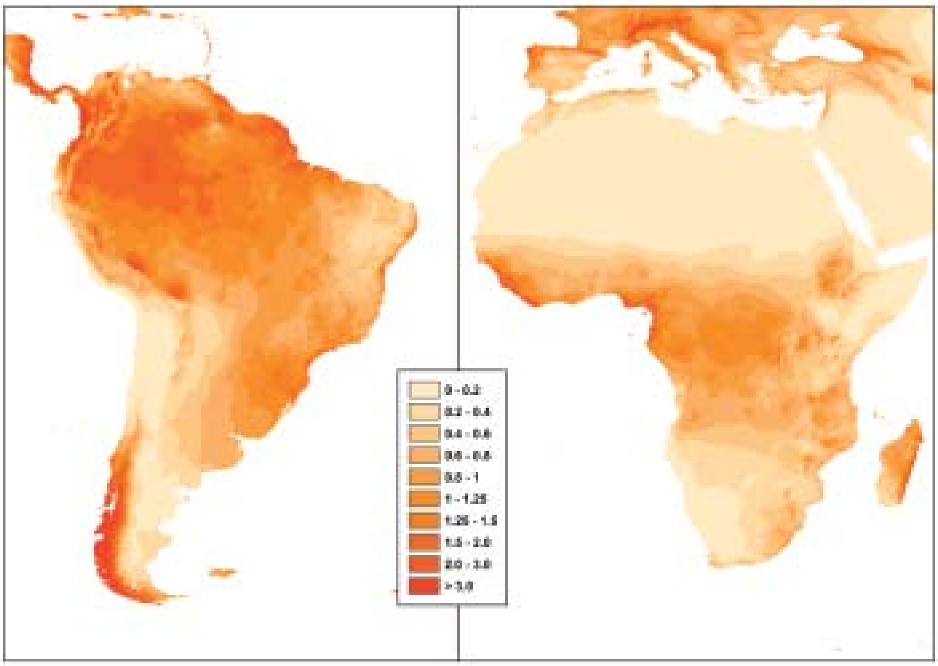


TABLE 6.
CDM-AR suitable land by NPP class given by area (Mha), and as percent (%) of the total suitable land, regionally and globally.

	NPP (tC/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	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
Southeast Asia	0.2	2.7	18.1	9.5	5.6	3.6	1.2	41
	CDM-AR Suitable Land Area (Mha)							
Global	14	149	314	161	59	16	12	725
Region	Percent of Total Regional CDM-AR Suitable Land Area (%)							
East Asia	7	67	21	5	1	0	0	
Sub-Sahara 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	
Southeast Asia	0	7	44	23	14	9	3	
	Percent of Global CDM-AR Suitable Land Area (%)							
Global	2	21	43	22	8	2	2	

almost all available land in South America (92 percent), South Asia (96 percent) and East Asia (98 percent), indicated a NPP less than 10 tC/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.

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, available at http://csi.cgiar.org/encofor/. Results are given on a country by country basis, with maps, tables, and graphs of the delineated area and its socio-ecological characteristics presented. In addition, the search tool allows the user to specify the crown cover density threshold to be used as ‘forest definition’ (Verchot et al. 2006), and whether or not to include protected areas (which includes national parks and other bioreserves) within the area deemed suitable for afforestation and reforestation.

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 LULUCF activities under Article 12 (UNFCCC 2002a; UNFCCC 2002b), specifically excluding activities such as avoidance of deforestation, improved forest management, or agricultural activities that build up carbon, such as conservation farming. Eligible projects have to represent a real land use change from non-forest into forest, or agroforestry, thus preventing current forests being converted into plantations (Smith and Scherr 2002).

In response to widespread concerns that CDM sink projects would impact negatively on CO_2 emission reduction aims (Greenpeace 2003), a cap on CDM-AR emission reduction offsets was set at one percent of the total global emission reduction target. The limit on the use of sink projects under the CDM implies that the annual flow of Certified Emissions Reductions (CERs) from afforestation and reforestation under Article 12 has an upper limit of 32.6 megatonnes of Carbon (Mt C), representing 119.6 megatonnes of Carbon Dioxide (Mt CO_2) equivalents, based on UNFCCC emission figures (Kolshus 2001). 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 to 8 tC/ha/yr), based on a literature survey of tropical tree plantation growth rates and the IPCC guidelines (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. Assumptions incorporated into this estimate include accounting for baseline and the lower productivity of marginal or degraded areas. It is further 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 is a relatively small figure, representing less that 1-2 percent of the area we have identified as suitable. CDM-AR is likely to be relatively small compared to globally suitable area estimates, and be geographically dispersed, both nationally and globally. Although small compared to the total global suitable area estimate, the total amount of land, and the potential funds made available for development, can be significant, both locally and nationally, depending upon rate of adoption, and especially dependent upon the market price for CERs.

Water use impact of CDM-AR

Land use changes resulting from the adoption of CDM-AR involve alterations of the hydrological cycle, both on flows of water and sediment and in situ vapor flow. Both, the relative impact on water cycles and absolute change in the quantity of water moving away from the site either as vapor or runoff, were quantified and mapped in this analysis. Together they indicate that large areas deemed suitable for CDM-AR would exhibit significant increases in vapor flow (figure 6) and/ or substantial decreases in runoff (figure 7). This is particularly evident in drier areas, the semi-arid tropics, and in conversion from grasslands and subsistence agriculture. Significant variation amongst biomes and bioclimatic zones is evident. However, almost 20 percent (144 Mha) of all suitable land showed little or no impact on runoff with another 28 percent (210 Mha) showing only moderate impact (table 7).

FIGURE 6.
Increases in vapor flow resulting from landuse change to CDM-AR, are given both in absolute terms (mm), and as the percentage increase (%) from existing landuse. Vapor flow includes both the *AET* and *Int* components of the water balance model.

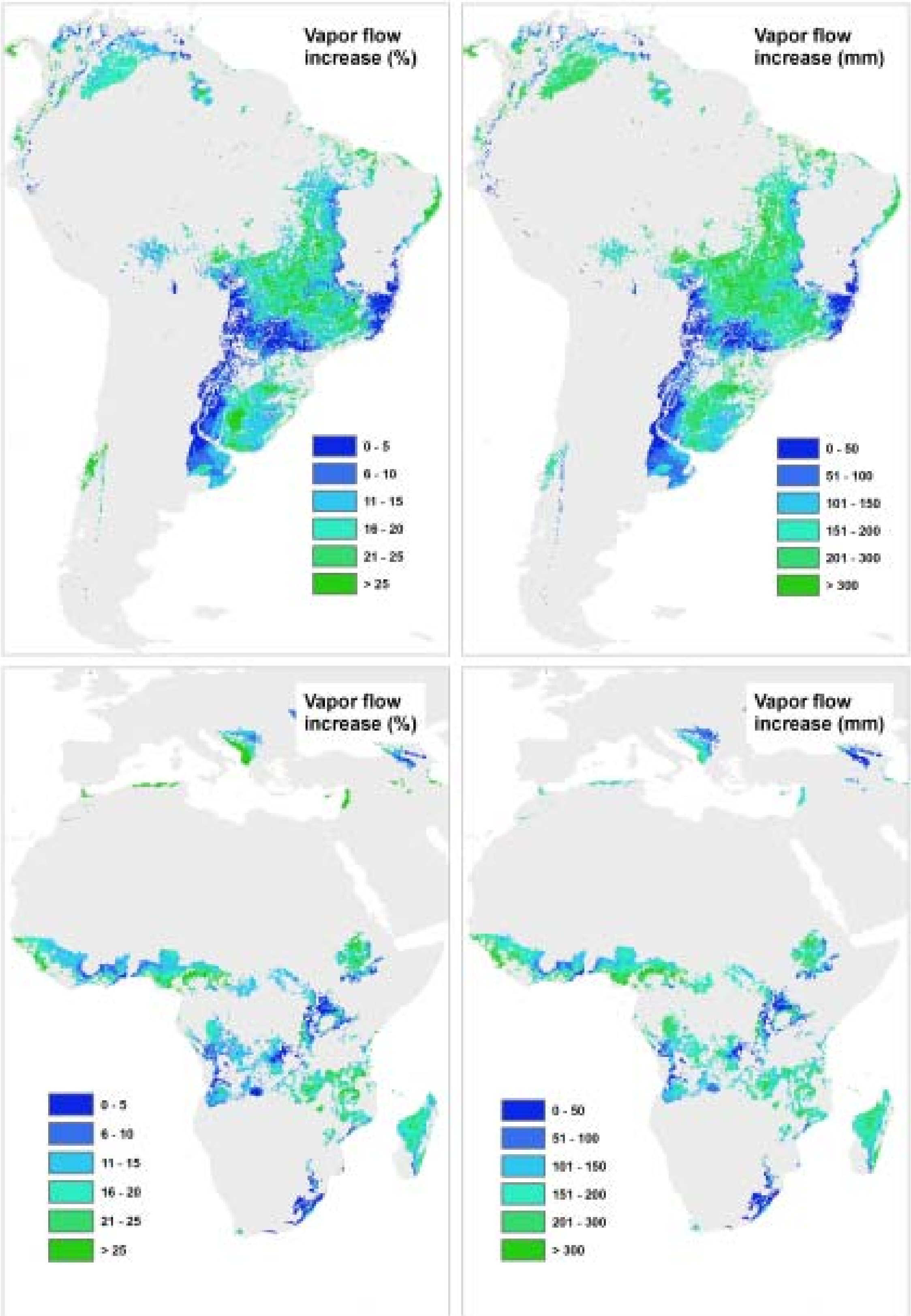


FIGURE 7.
Decreases in runoff resulting from landuse change to CDM-AR, are given both in absolute terms (mm), and as the percentage decrease (%) from existing landuse.

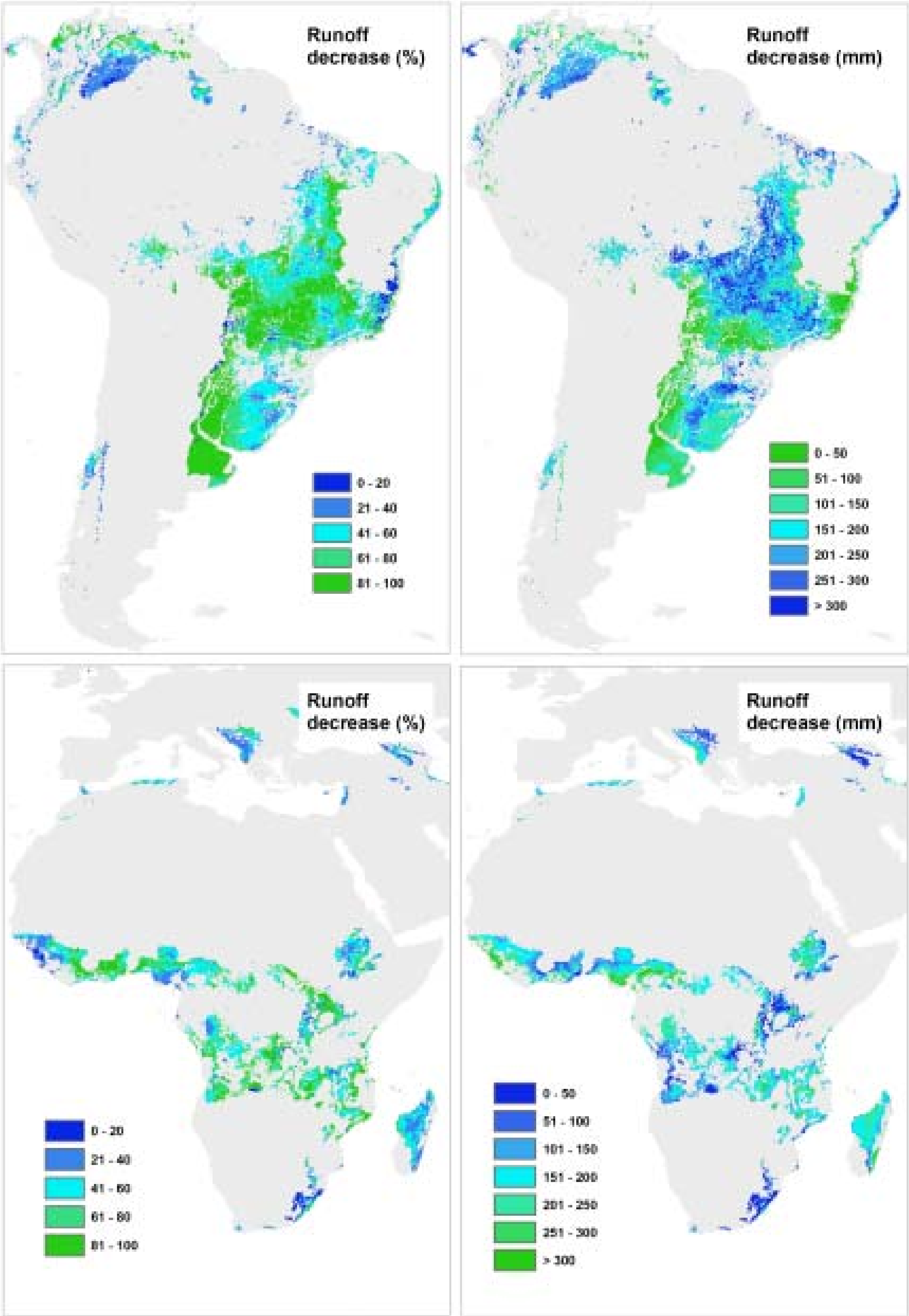


TABLE 7.
Decrease in total runoff (mm) and percent decrease (%) in total runoff with landuse change to CDM-AR on suitable land, regionally and globally.

	Decrease in Runoff (mm)							
	0-50	50-100	100-150	150-200	200-250	250-300	300-400	> 400
Region	(Mha)							
East Asia	16	14	10	16	18	7	2	1
Sub-Sahara Africa	15	19	45	67	30	12	9	2
South America	38	42	57	81	72	38	27	5
South Asia	0	1	2	8	9	12	27	6
Southeast Asia	0	1	2	3	3	3	8	11
	(Mha)							
Global	69	76	116	175	132	73	72	25

	Decrease in Runoff as a Percent of Total (%)				
	0-20	20-40	40-60	60-80	80-100
Region	(Mha)				
East Asia	6	10	25	21	22
Sub-Sahara Africa	0	13	11	3	2
South America	3	12	22	19	9
South Asia	7	33	58	53	48
Southeast Asia	11	48	94	87	119
	(Mha)				
Global	28	116	210	183	200

Taken together 50 percent of all suitable land showed a decrease in runoff of less than 60 percent (figure 4f). About 27 percent (200 Mha) is in the highest impact class exhibiting an 80-100 percent decrease in runoff. Altogether, almost 60 percent showed a decrease of less than 200 mm, with only slightly more than 13 percent showing a decrease of more than 300 mm (figure 4g). Since it is reasonable to assume that only a small proportion of these lands would be converted to forestry land use types, it is unlikely that global scale or even major regional impacts would be evident in the aggregated statistics. Further, with the cap on CDM-AR at one percent, estimated by this study to be satisfied by at most conversion of a mere 2 percent of available land, direct impacts of CDM-AR at the global and regional scales are unlikely. However, significant changes in CDM rules affecting the number of carbon sink projects, or amount of land which will eventually be under CDM-AR, should take into account these potential impacts on the hydrological cycle.

Local Scale Water Use Impact of CDM-AR

At the local and project level, impacts were estimated to be substantial and important. Land use change to CDM-AR in all of the four study sites showed strong spatial variations of runoff and changes in SWC. While reduced runoff is clearly linked to reduced downstream water supply, variation in SWC is also important because it implies a likely associated variation in groundwater tables. It is usually assumed that most, if not all, base flow is supplied by groundwater circulation, and initially by downward flows associated with SWC above field capacity. Streams that receive large proportions of their flow as groundwater base flow tend to have relatively low temporal flow variability and hence provide a more reliable source of water for various water-resource purposes (Dingman 1993). All four sites showed a marked reduction in runoff, with both on-site and off-site implications (table 8). On the humid lowland tropical Amazon site in Chapare, Bolivia (figure 8), the impact of the reduction was minimal, since precipitation is high and not a limiting factor. By contrast, the drier high elevation Tunari site in Bolivia (figure 9) showed significant decrease (28 percent) in runoff. There was relatively little impact on soil water content since these denuded slopes already have a very low water holding capacity under the existing land use. At this site, recurrent flooding due to excessive runoff from eroded slopes during the rainy season is a major problem for the adjacent city of Cochabamba, thus decreased runoff and lowered water tables as demonstrated in this study are considered positive. Thus, tree planting for the Tunari site is shown to be an effective means to provide multiple benefits such as conservation and flood mitigation. In the Guamote case study, in the highland Sierras of Ecuador (figure 10), the water implications of afforestation with pine trees is already a controversial issue (Farley et al. 2004). In addition to a large decrease in runoff (54 percent), there also appears to be a significant impact on the soil water content (decrease of 32 percent), indicating a likelihood of decreasing water table levels over time. Increases in *AET* and total vapor flows are relatively small, since this system is already water limited under current land use. As predicted in this case, common consequences of afforestation projects using fast-growing conifers are decreased levels of stream flow, both over the entire year (Swank and Douglass 1974) and during the dry season (Vincent 1995). Likewise, the reduction in runoff associated with conversion of pasture to mixed tropical indigenous agroforestry in coastal Ecuador (figure 11) was relatively large (47 percent). However, again in this case, the generally higher level of precipitation and the site's downstream location within the catchment, minimized the importance of the decrease in runoff.

TABLE 8.
Results of water balance model applied at local scale for four case studies. Project area represent the total area allocated to the project, and CDM-AR area is the total area within the project area suitable for CDM-AR. Vapor flow is given as the sum of *AET* and *Int*, in order to represent total ET, and is presented as the percent increase resulting from landuse change to CDM-AR. Runoff and *SWC* are given as the percent decrease resulting from landuse change to CDM-AR.

CDM-AR Project	Project Area (ha)	CDM-AR Area (ha)	Precip (mm/yr)	Aridity Index (Mean AI)	Vapor Flow Increase (%)	Runoff Decrease (%)	SWC Decrease (%)
Tunari NP, Bolivia	32,142	9,873	900	0.8	7.1	27.7	7.3
Chapare, Bolivia	40,604	11,077	3,000	1.8	15.1	12.4	1.1
Guamote, Ecuador	15,104	13,327	700	0.6	4.7	54.0	32.0
Coastal Ecuador	41,878	26,564	1,300	0.9	23.4	47.4	13.4

Note: Precip=Precipitation.

FIGURE 8.
Chapare Case Study: (a) CDM-AR suitable land; (b) increase in vapor flow (*AET* and *Int*) with landuse change to CDM-AR; (c) decrease in *SWC* with landuse change to CDM-AR; (d) decrease in Runoff with landuse change to CDM-AR; and (e) representative view of the project area, showing a mixed farming landscape typical of this area in the Bolivian Amazon.

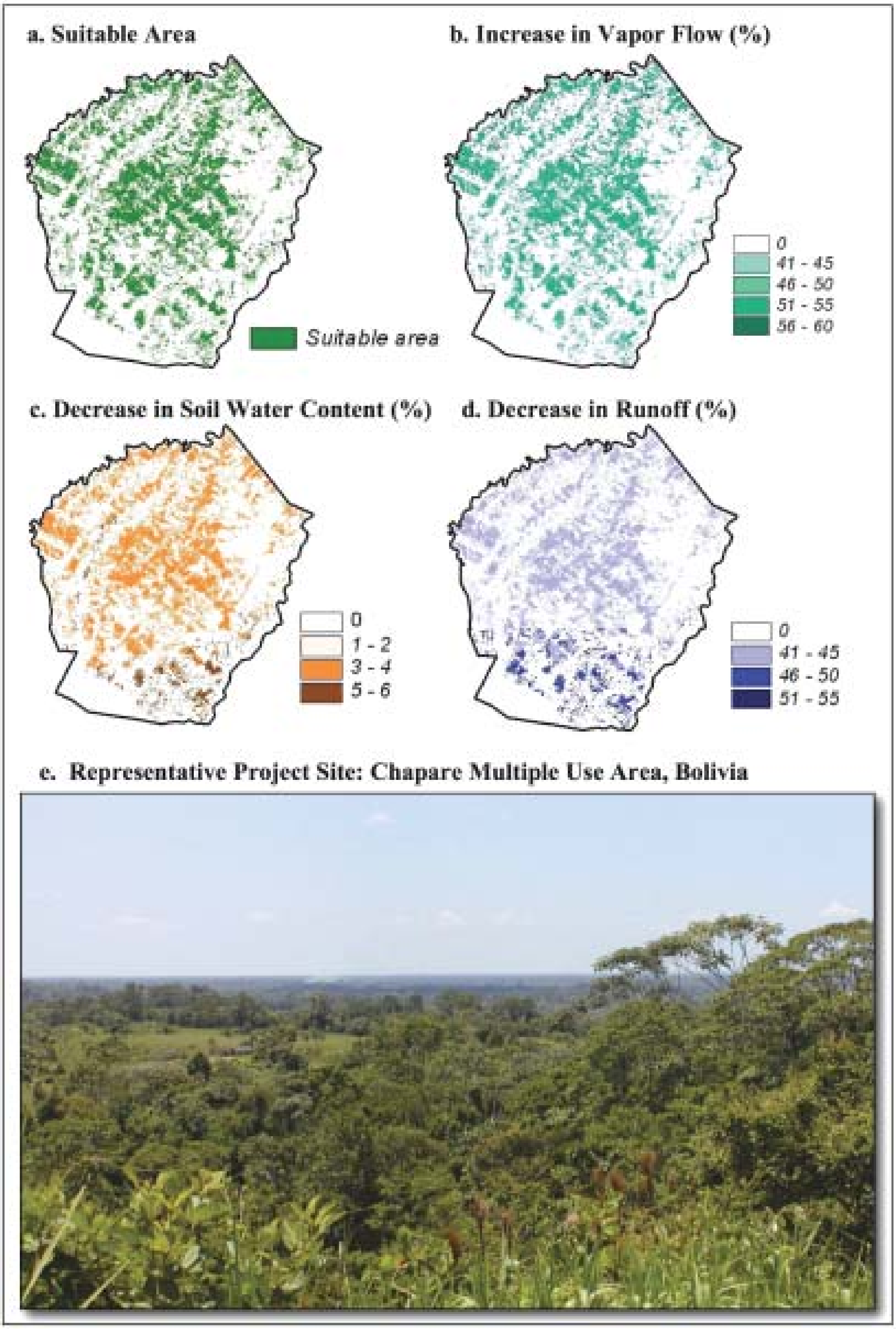


FIGURE 9.
Tunari Case Study: (a) CDM-AR suitable land; (b) increase in vapor flow (*AET* and *Int*) with landuse change to CDM-AR; (c) decrease in *SWC* with landuse change to CDM-AR; (d) decrease in Runoff with landuse change to CDM-AR; and (e) view of reforestation with pine in the Tunari National Park, with the city of Cochabamba below.

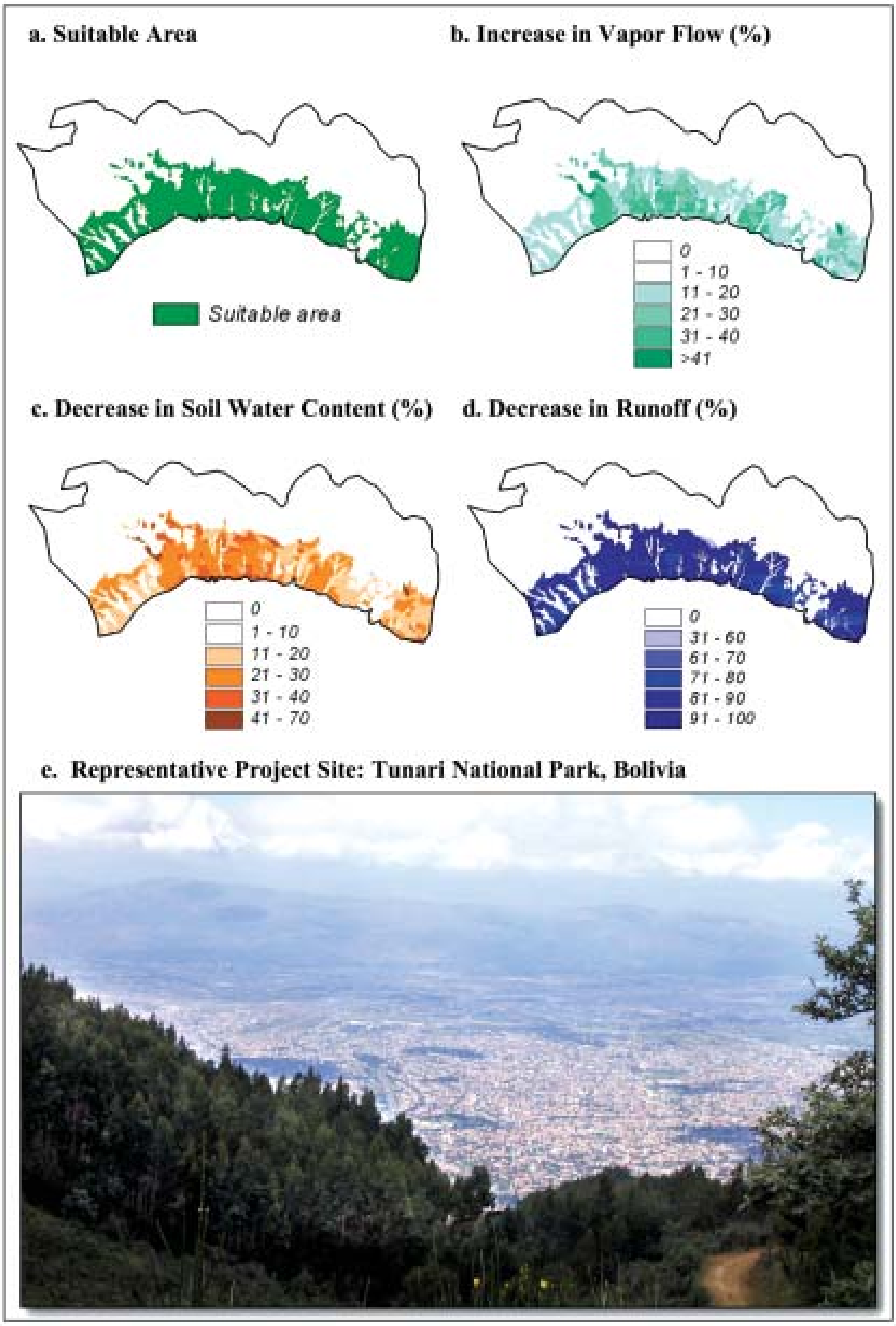


FIGURE 10.
Guamote Case Study: (a) CDM-AR suitable land; (b) increase in vapor flow (*AET* and *Int*) with landuse change to CDM-AR; (c) decrease in *SWC* with landuse change to CDM-AR; (d) decrease in Runoff with landuse change to CDM-AR; and (e) community-owned afforestation projects in one of the poorest regions in the highlands of Ecuador.

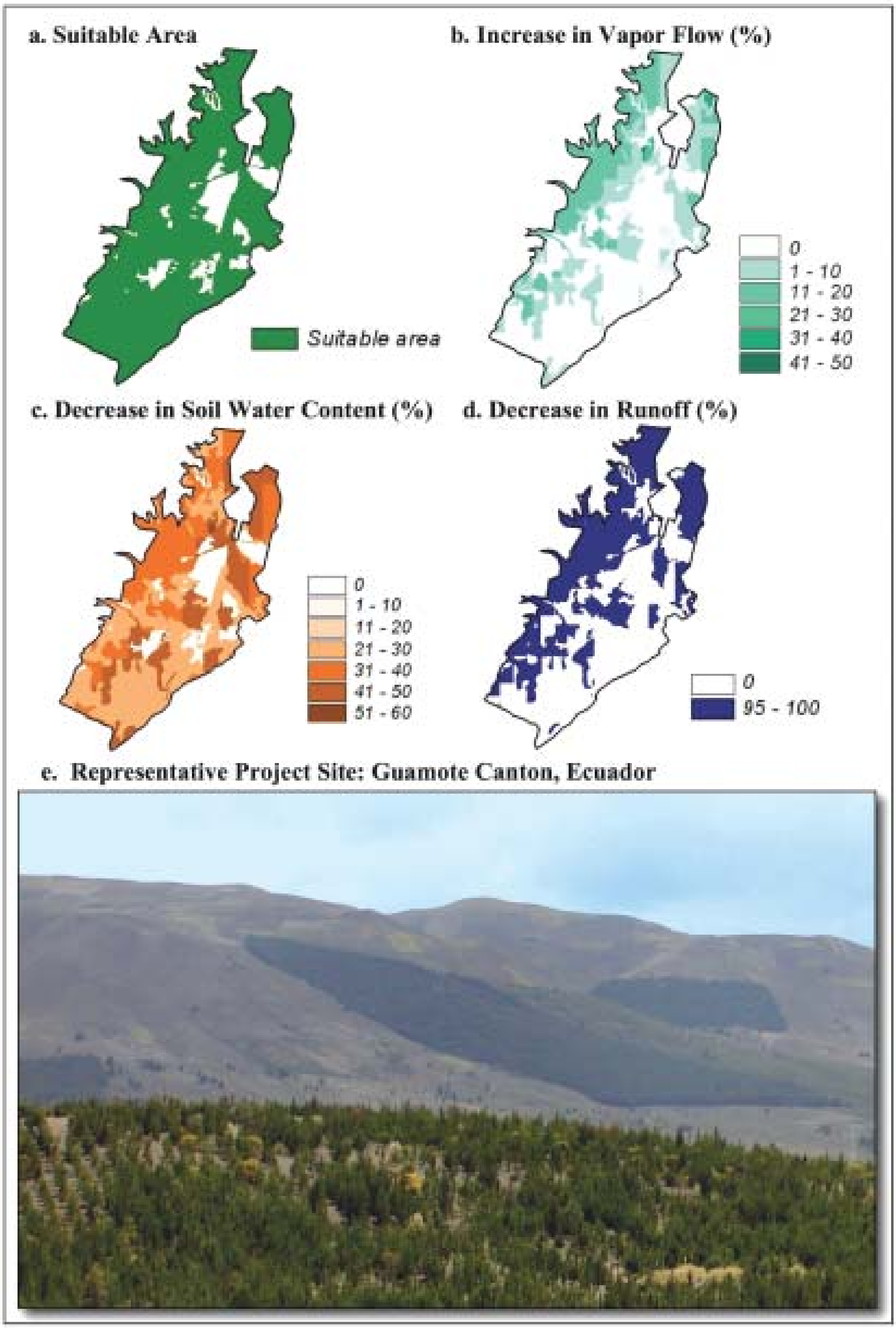
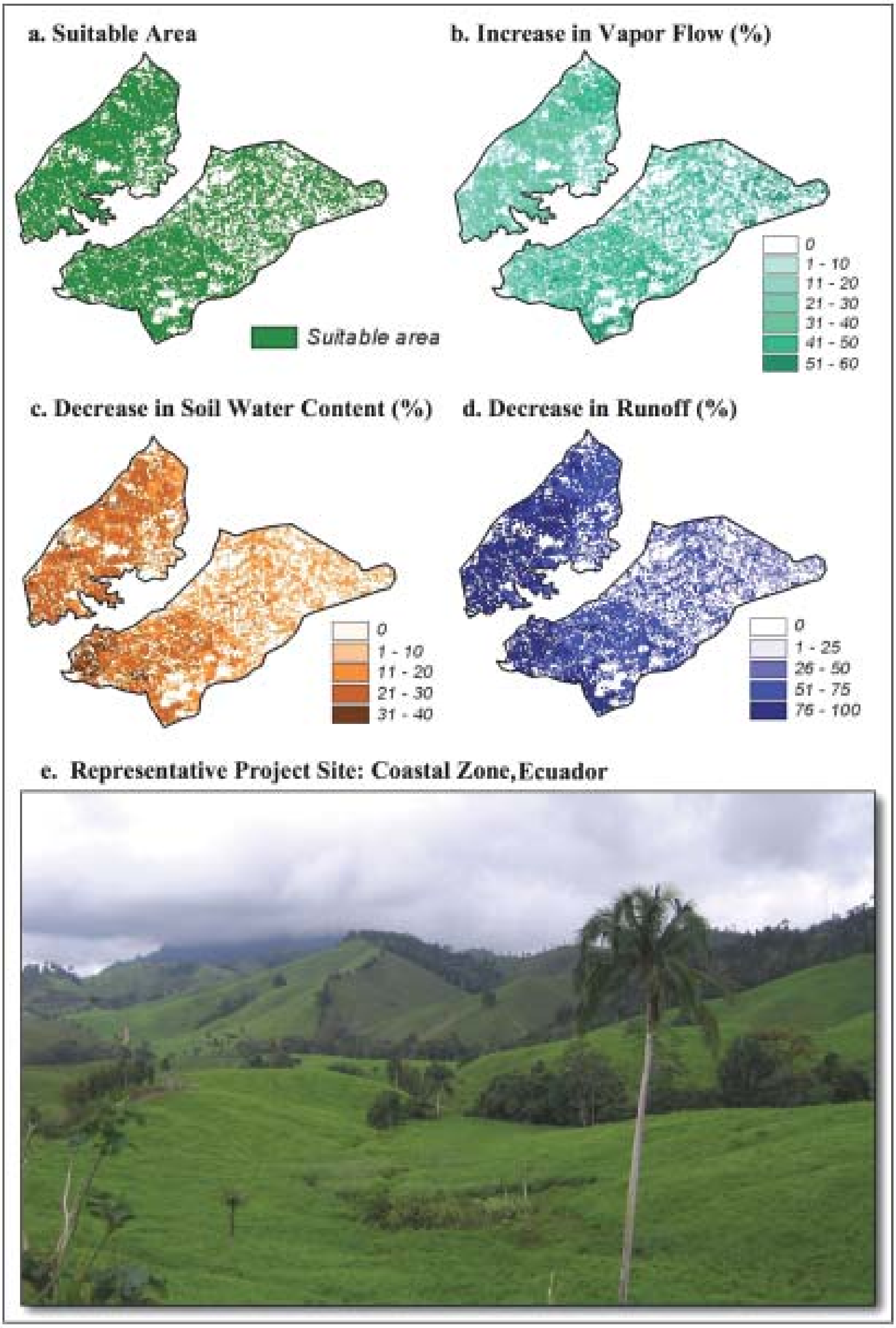


FIGURE 11.
Coastal Ecuador Case Study: (a) CDM-AR suitable land; (b) increase in vapor flow (*AET* and *Int*) with landuse change to CDM-AR; (c) decrease in *SWC* with landuse change to CDM-AR; (d) decrease in Runoff with landuse change to CDM-AR; and (e) pastures throughout the humid tropics offer opportunities for increasing carbon baselines.



In general, the results indicate that, although impacts may not be discernable at the global or regional level, CDM-AR projects have large and significant local impacts on water use, with both on-site and downstream implications. Investigation of these four case studies illustrates that both local effects, and desired outcomes, are highly site specific and highlights the importance of considering hydrologic implications of land use change, when evaluating, planning and implementing CDM-AR.

Conclusion

This report highlights that there is an abundance of land for, and potentially significant impacts resulting from, climate change mitigation measures, particularly on the hydrologic cycle. The global impact of redistribution of water use driven by agriculture and land use change, of which CDM-AR can be a contributing factor, is a major component of ongoing global change, with high significance in terms of impact on climate change processes. The CDM-AR hydrological impact analysis shows significant impacts on local and regional hydrologic cycles, although they are not evident at regional or global scale under current rules which limit the amount of sink projects to a one percent cap. If the cap on CDM-AR were raised to compensate for a substantially greater offset of carbon emission through sink projects, it is suggested that it will be increasingly important to consider implications on local to regional water resources. Although not currently of this same magnitude (i.e., under the one percent cap), this important dimension of CDM-AR should be formally articulated and taken into account within the CDM-AR guidelines, especially when addressing issues of sustainability, local communities, and food security.

The potential for small farmers and communities to participate in CDM-AR has been highlighted and promoted by developing countries and NGOs. In particular, the adoption of agroforestry type practices has been put forward as a way for smaller farmers and communities to participate in CDM-AR projects. This may constitute an option for significantly increasing the carbon sequestration within rural and agricultural landscapes, while contributing positively to increased food and household security. 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. As such, there are indeed both national and local food security considerations that must be taken into account in proposing CDM-AR development activities. 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 (Gupta et al. 2005) demonstrate that small-scale wood plantations and agroforestry can substantially increase carbon stocks with significant positive benefits for rural communities. In this case, where intensively cultivated irrigated areas are being converted to agroforestry, afforestation provides added security to small farmer livelihoods by offering alternate production opportunities and diversification.

The afforestation of upland catchments with fast growing plantations can have significant impact on in situ water use, with consequent impacts on water availability downstream. Generally, CDM-AR results in an increase of AET, or 'green water' vapor flows, increased on-site water use, and decreased movement of water and sediments off-site. However, whether this is a positive or negative impact on water resources, water management, soil and land conservation, biodiversity, and/or downstream food security, is highly site specific, and dependent upon climate, soil types, topography, land uses, population densities, existing infrastructures, and tradeoffs with coexisting demands for water. Whereas trees do use more water than many other vegetation forms and most crops, this analysis has shown that the variability in response is highly dependent on the specific ecological characteristics of the site, and that globally, there are large areas of land where impacts of CDM-AR on water resources and food security will be minimal. On a national and local basis, the selection of CDM-AR sites can take into consideration these specific hydrologic and socio-ecological aspects, to evaluate increased green water vapor flows and associated decreases in runoff, and to identify optimal conditions and locations which minimize negative aspects. Projects can even capitalize on the positive aspects of these potential impacts, for instance, in reducing recurrent flooding, or sediment transfer.

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 the current cap on CDM-AR credits. It is likely that CDM-AR, and possibly other carbon sink approaches, will play a larger, increasingly more 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, and restoration of degraded forests, so that credits available from sink projects will increase. In addition, we highlighted here the 'hidden' water dimension associated with climate change mitigation efforts that can be found in many of the other global treaties and conventions addressing the various contemporary environmental and global issues. Articulating these 'secondary effects' on the hydrologic cycle is essential if we are to address these global concerns in a holistic fashion.

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