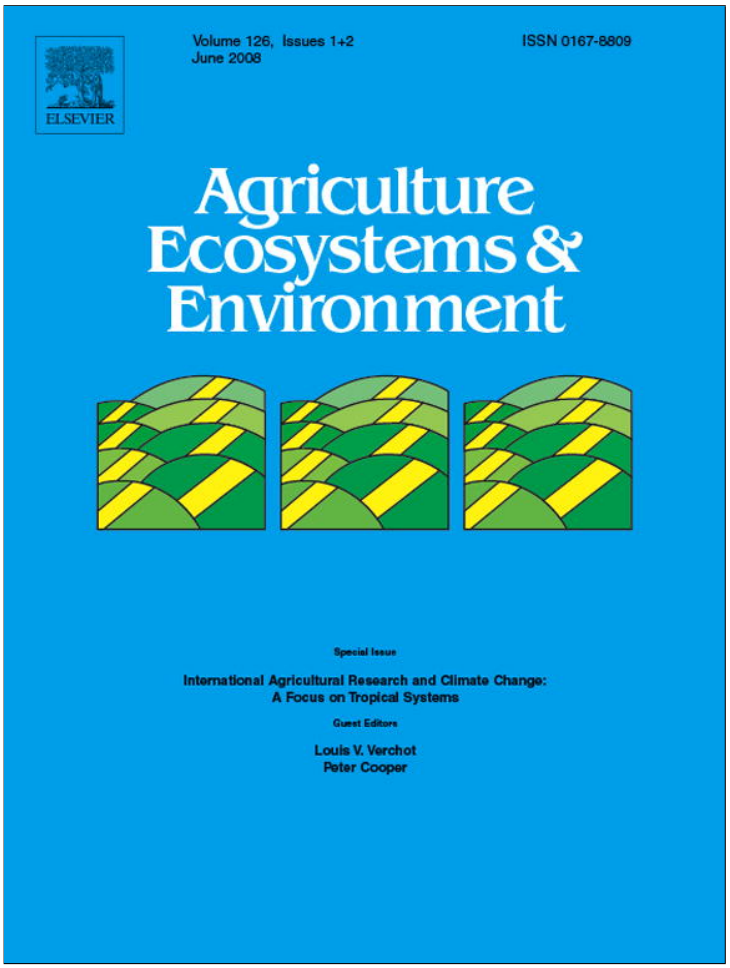
Provided for non-commercial research and education use.
Not for reproduction, distribution or commercial use.



This article appeared in a journal published by Elsevier. The attached copy is furnished to the author for internal non-commercial research and education use, including for instruction at the authors institution and sharing with colleagues.

Other uses, including reproduction and distribution, or selling or licensing copies, or posting to personal, institutional or third party websites are prohibited.

In most cases authors are permitted to post their version of the article (e.g. in Word or Tex form) to their personal website or institutional repository. Authors requiring further information regarding Elsevier's archiving and manuscript policies are encouraged to visit:

http://www.elsevier.com/copyright

Author's personal copy

Available online at www.sciencedirect.com
ScienceDirect
Agriculture, Ecosystems and Environment 126 (2008) 81–97
Agriculture Ecosystems & Environment
www.elsevier.com/locate/agee

Climate change mitigation through afforestation/reforestation: A global analysis of hydrologic impacts with four case studies

Antonio Trabucco [a,b], Robert J. Zomer [c,*], Deborah A. Bossio [a], Oliver van Straaten [a,c], Louis V. Verchot [c]

[a] *International Water Management Institute (IWMI), P.O. Box 2075, Colombo, Sri Lanka*
[b] *Forest Ecology and Management, Division Forest, Nature and Landscape-K.U. Leuven, Celestijnenlaan 200E, BE-3001 Leuven, Belgium*
[c] *World Agroforestry Centre (ICRAF), P.O. Box 30677, Nairobi, Kenya*

Available online 4 March 2008

Abstract

The implicit hydrologic dimensions of international efforts to mitigate climate change, specifically potential impacts of the Clean Development Mechanism-Afforestation/Reforestation (CDM-AR) provisions of the Kyoto Protocol (KP) on global, regional and local water cycles, are examined. The global impact of the 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 and climate change processes. If converted to forest, large areas deemed suitable for CDM-AR would exhibit increases in actual evapotranspiration (AET) and/or decreases in runoff. Almost 20% (144 Mha) of all suitable land showed little or no impact on runoff and another 28% (210 Mha) showed only moderate impact. About 27% (200 Mha) was in the highest impact class, exhibiting an 80–100% decrease in runoff, and prevalent in drier areas (based on *Aridity Index* (AI)), the semi-arid tropics, and in conversion from grasslands and subsistence agriculture. Significant impacts on local hydrologic cycles were evident, however large impacts were not predicted at regional or global scale due primarily to the current limit on carbon offset projects under the Kyoto Protocol. Predicted decreases in runoff ranged from 54% in drier areas to less than 15% in more humid areas, based on four case studies located across a range of biophysical conditions and project scenarios in Ecuador and Bolivia. Factors other than climate, e.g. upstream/downstream position, were shown to be important in evaluating off-site impacts. This study demonstrates that it will become increasingly important to consider implications on local to regional water resources, and how the hydrologic dimension of CDM-AR impacts on issues of sustainability, local communities, and food security.
© 2008 Elsevier B.V. All rights reserved.

Keywords: Climate change; Afforestation; Reforestation; Water; Hydrological modeling; Spatial modeling; Trees; Forests; Aridity Index; Potential evapotranspiration; CDM-AR; Clean Development Mechanism

1. Introduction

While much attention is being given internationally to the opportunities for carbon sequestration to mitigate climate change, little attention is being paid to the environmental tradeoffs that are associated with these types of schemes. This study seeks to 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 Kyoto Protocol (KP) on global, regional and local water cycles. CDM-AR allows for carbon sequestration offsets to meet emission reduction obligations for the developed countries, through the purchase of 'carbon credits' from afforestation or reforestation projects in developing countries. Land use changes resulting from the adoption of CDM-AR involve alterations of the hydrological cycle, both on flows of water and sediment, and levels of actual evapotranspiration (AET) or vapor flows.

Water supply and scarcity has received increasing attention over the last decade, primarily driven by alarming

* Corresponding author. Tel.: +254 20 7274000.
E-mail address: r.zomer@cgiar.org (R.J. Zomer).

0167-8809/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.agee.2008.01.015

Author's personal copy

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 demand for agriculture must rise between 12 and 27% by 2025 to meet growing food needs (IWMI, 2000; FAO, 2001b, 2003a,b; 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 already suffer from diversions of water for food production. There will be increasing conflicts between the need for water diversions to agriculture and water needs for maintaining aquatic ecosystems. Environmental flow requirements (Smakhtin et al., 2004) are increasingly being taken into account to manage water allocations, to allow for the ecosystem requirements 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 with global climate change mitigation strategies, are as yet rarely considered in these discussions. This is partly due to an under-appreciation that carbon fixation through biomass production increases vapor flows, and requires consumption of water that may not then be available for other uses. A historical hydrological bias (Andréassian, 2004) 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 been the subject of much interest and research (Andréassian, 2004; Bruijnzeel, 2004; CIFOR and FAO, 2005), most recently 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) and Rockstrom et al. (1999), and in the forestry sector by Calder (2000). Green water is defined as that portion of precipitation that is not available for either surface water flows or groundwater recharge, namely soil moisture that potentially will either evaporate from the soil or transpire to the atmosphere through plants fixing carbon (i.e. evapotranspiration). Only recently have a few studies highlighted the implications of global climate change mitigation strategies on water use and vapor flows (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 into sharp focus.

We know that tree removal by logging, forest fire, or wind damage increases runoff (Bosch and Hewlett, 1982; Bormann and Likens, 1995; Andréassian, 2004). Jackson et al. (2005) found that plantations decreased stream flow by 227 millimeters per year globally (52%), with 13% of streams drying completely for at least 1 year. The magnitude of this water flow 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 volume of the root zone from which water is extracted under trees (Dingman, 1993). A review of catchment experiments (Bosch and Hewlett, 1982) found that, on the average, pine and eucalypt plantations cause a 40 mm decrease in runoff for any 10% 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). However, 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, increased control over nutrient fluxes, decreased sediment loads, increased water quality); 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, e.g. through flow regulation and decrease of flood risk.

In this study, we analyze the water use implications of CDM-AR at two scales: global and local. The potential hydrologic impacts of these carbon offset (or ''carbon sink'') mitigation approaches, are modeled and estimates of water balance and vapor flow response to a land use change to forestry activities is reported. A simple water balance approach, combined with the results of the land suitability analysis (Zomer et al., 2008) is used to estimate impacts on hydrological cycles resulting from a change to forestry activities.

Specific objectives:

(1) To estimate potential impacts of adoption of CDM-AR on global to regional hydrologic cycles.
(2) To estimate potential impacts of adoption of CDM-AR on local hydrologic cycles based on four case studies of proposed CDM-AR projects.

Author's personal copy

2. Methods

2.1. Hydrologic analysis

The suitability of CDM-AR within a particular setting, is constrained by the current UNFCCC guidelines (UNFCCC, 2002a,b) for CDM-AR projects within the first commitment period (2007–2012), notably forest definition (Verchot et al., 2007), and a complex of biophysical and socio-economic factors necessary for a sustainable, socially equitable, and economically viable tree growing enterprise. In this study, we use the result of a global analysis of land suitability for CDM-AR (Zomer et al., 2008) as the basis to articulate potential hydrologic impacts. This analysis identified large amounts of land (749 Mha) that satisfy the UNFCCC CDM-AR eligibility criteria, and are biophysically suitable for afforestation or reforestation based on climatic and land use factors. The water balance model was applied to a high resolution global dataset, on a per pixel basis, using a spatial modeling procedure developed and implemented in ArcGIS (ESRI Inc.) using ArcAML programming language. The model is applied on a per pixel basis to estimate spatially disaggregated biophysical conditions within areas found suitable for CDM-AR, and to predict hydrologic changes with conversion of these suitable areas to afforestation or reforestation. Environmental and other global geospatial datasets used within the global analysis (spatial resolution: 500 m to 1 km, 15–30 arc-s) include:

• VMAP 1—Country boundaries	(NIMA, 1997)
• WorldClim	(Hijmans et al., 2004)
• Maximum available soil water	(Digital Soil Map of the World—FAO, 1995)
• Climate station dataset	(FAOCLIM—FAO, 2001a)
• Global map of ecosystem rooting depth	(ISLSCP—Schenk and Jackson, 2002)

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, which accurately represents area across latitudes (equal-area projection), was used to calculate zonal statistics and carry out areal computations. The cell size for analyses in geographic projection is equal to 0.004497° (15 arc-s, ~1 km at equator and 500 m at 60° latitude), while the cell size for analyses in sinusoidal projection is 500 m.

2.2. Water balance model

A spatially distributed Thornthwaite–Mather water balance modeling approach (Thornthwaite, 1948; Thornthwaite and Mather, 1955) was used to examine hydrological differences in actual evapotranspiration, soil water content (SWC) 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. 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:

$$\Delta \mathrm{SWC}_m = \mathrm{Eprec} + \mathrm{Irr}_m - \mathrm{AET}_m - R_m \quad \mathrm{mm/month} \tag{1}$$

where $\Delta \mathrm{SWC}_m$ 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, $\mathrm{SWC}_{\max}$, which is the total SWC available for evapotranspiration (ET).

Therefore, the SWC at the end of the month, $\mathrm{SWC}^{\mathrm{f}}_m$ is equal to:

$$\mathrm{SWC}^{\mathrm{f}}_m = \begin{array}{ll} \mathrm{SWC}^{\mathrm{b}}_m + \mathrm{Eprec}_m + \mathrm{AET}_m - R_m & \text{if} \quad \mathrm{SWC}^{\mathrm{f}}_m < \mathrm{SWC}_{\max} \\ \mathrm{SWC}_{\max} & \text{if} \quad \mathrm{SWC}^{\mathrm{f}}_m \geq \mathrm{SWC}_{\max} \end{array} \tag{2}$$

where $\mathrm{SWC}^{\mathrm{b}}_m$ is the soil water content at the beginning of the month. The SWC at the end of the month, $\mathrm{SWC}^{\mathrm{f}}_m$, is set as the SWC at the beginning of the following month, $\mathrm{SWC}^{\mathrm{b}}_{m+1}$. All the water exceeding $\mathrm{SWC}_{\max}$ is accounted as runoff:

$$R_m = \begin{array}{ll} \mathrm{SWC}^{\mathrm{b}}_m + \mathrm{Eprec}_m - \mathrm{AET}_m - \mathrm{SWC}_{\max} & \text{if} \quad \mathrm{SWC}^{\mathrm{b}}_m + \mathrm{Eprec}_m - \mathrm{AET}_m > \mathrm{SWC}_{\max} \\ 0 & \text{if} \quad \mathrm{SWC}^{\mathrm{b}}_m + \mathrm{Eprec}_m - \mathrm{AET}_m \leq \mathrm{SWC}_{\max} \end{array} \tag{3}$$

Method of calculation for the component terms in these formulas are explained in the following sections.

Author's personal copy

2.3. Monthly potential evapotranspiration

Potential evapotranspiration 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 cm, a fixed surface resistance of 70 s/m and an albedo of 0.23 (Allen et al., 1998). Five different methods of calculating PET were tested to determine which equation performed the best for the objectives of this analysis: Thornthwaite (1948), Thornthwaite modified by Holland (1978), Hargreaves et al. (1985), Hargreaves modified by Droogers and Allen (2002), and the FAO Penman–Monteith global dataset (Allen et al., 1998) at 20 km resolution (available online). Values for PET calculated using each of the above five methods were compared to PET values for specific climate stations calculated using climate station data ($n = 2288$). These PET values are calculated using the more complex Penman–Monteith model applied on direct observations of the various climatic parameters, and were obtained from the FAOCLIM climate station dataset (Allen et al., 1998), available online from FAO. Based on the results of the comparative validation (Table 1), for South America (Fig. 1) and Africa (Fig. 2), the Hargreaves model was chosen to model PET globally for this study. This method performed almost as well as the FAO Penman–Monteith method, but required less parameterization, and had significantly lower 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–Monteith 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:

$$\mathrm{PET} = 0.0023 \cdot \mathrm{RA} \cdot (T_{\mathrm{mean}} + 17.8) \cdot \mathrm{TD}^{0.5} \quad (\mathrm{mm/d}) \tag{4}$$

2.4. Actual evapotranspiration and green water vapor flows

Actual evapotranspiration 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):

$$\mathrm{AET}_m = K_{\mathrm{veg}} \times K_{\mathrm{soil}} \times \mathrm{PET}_m \quad \mathrm{mm/month} \tag{5}$$

where K_{veg} = vegetation coefficient dependent on vegetation characteristics (0.3–1.3); K_{soil} = reduction factor dependent on volumetric soil moisture content (0–1).

The vegetation coefficient (K_{veg}) is used to calibrate the reference PET for different crops or vegetation types. K_{veg}

Table 1
Five different methods for calculating PET were compared and tested to determine which performed best to meet the objectives of a global spatial analysis at a high resolution (i.e. 1 km): Thornthwaite (1948), Thornthwaite modified by Holland (1978), Hargreaves et al. (1985), Hargreaves Modified by Droogers and Allen (2002), and the FAO Global Penman–Monteith Spatial Dataset (Allen et al., 1998) with a resolution of 20 km

Region	Month	Comparison of five methods used to estimate PET									
		Holland (Thornthwaite)		Thornthwaite		Hargreaves		Modified Hargreaves		Penman–Montieth FAO	
		Mean diff.	S.D.	Mean diff.	S.D.	Mean diff.	S.D.	Mean diff.	S.D.	Mean diff.	S.D.
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 temperature		Available online from FAO	
						Average extraterrestrial radiation		Average extraterrestrial radiation			
						Average temperature range		Average temperature range			
								Average precipitation			

Results are given as the mean difference (Mean diff.) (mm) between observed and predicted estimates, and their standard deviations (S.D., (mm)).

Author's personal copy

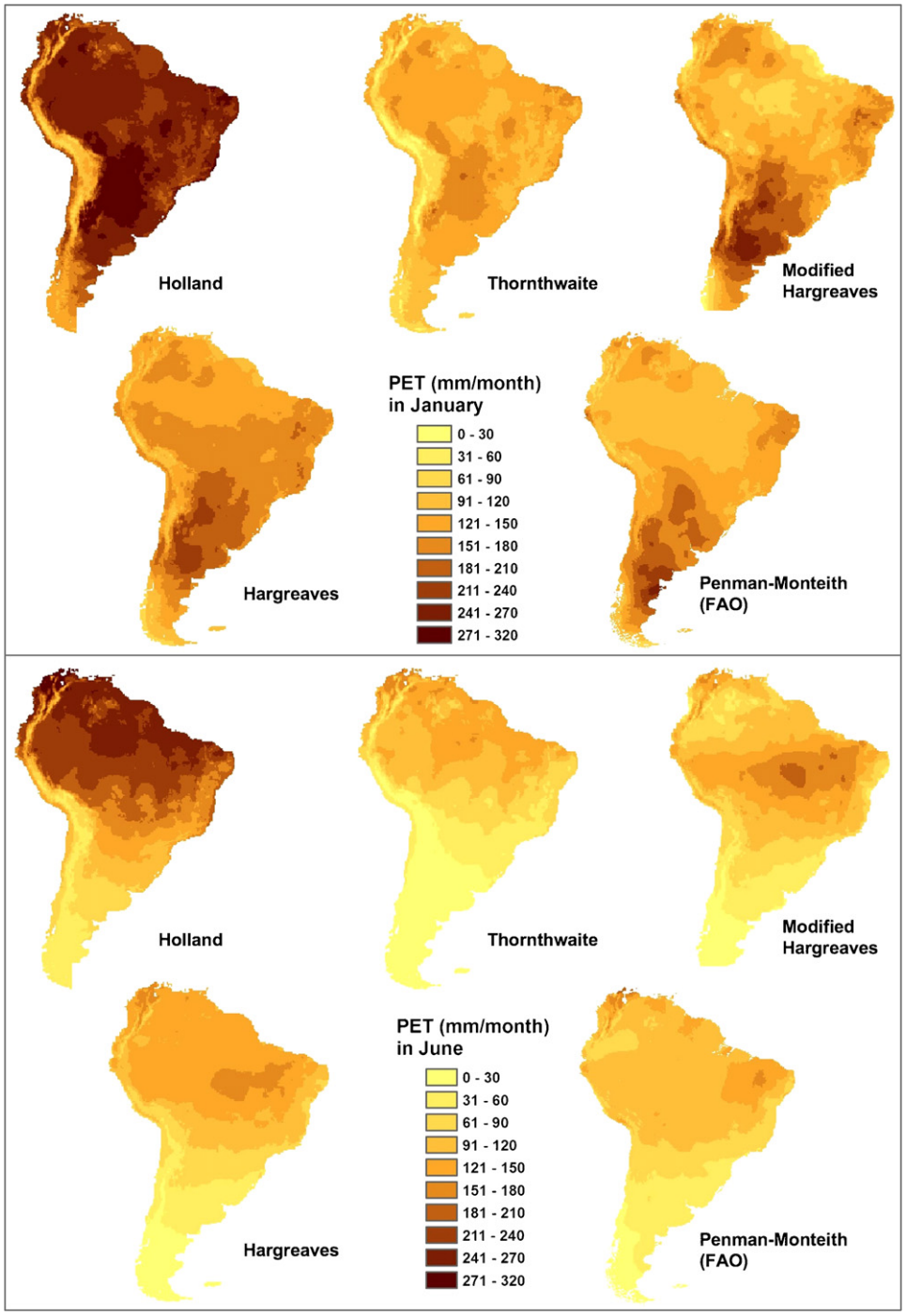


Fig. 1. Results from five different methods of calculating PET for South America during two seasons.

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.

$$SWC_{max} = RD \times (SWC_{fc} - SWC_{wp}) \quad (6)$$

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).

Author's personal copy

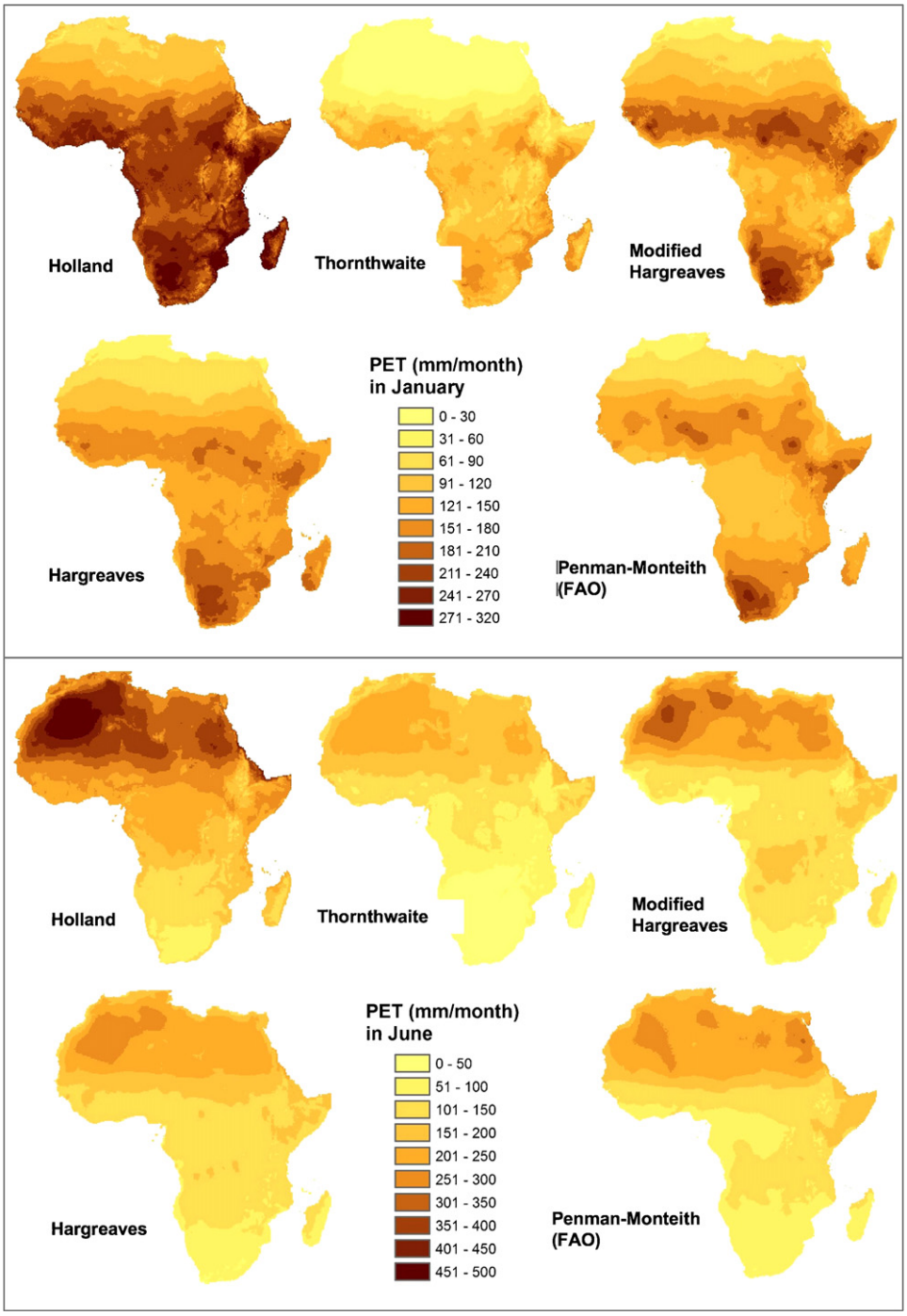


Fig. 2. Results from five different methods of calculating PET for Africa during two seasons.

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 the rooting depth of six specific vegetation classes, namely Trees, Shrubs, Pasture, Grass, Crop and Bare Land, under non-water stress conditions, based upon their estimated occurrence within specific land use types. Rooting depth of vegetation is likely to be deeper under water stressed conditions, as water is stored more at depth in the soil during dry seasons. Rooting depths values for vegetation types under 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

Author's personal copy

absolute volumetric soil water content. The model uses a simple linear soil moisture stress function that is considered appropriate for monthly computation (Dyck, 1983):

$$K_{\text{soil}_m} = \text{SWC}_m / \text{SWC}_{\max} \quad (7)$$

SWC_m = soil water content averaged over the month.

2.5. Effective precipitation

Effective precipitation, that part of precipitation that adds water 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, calculated as a fraction of Gprec. 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 (Int) has an important role in the water budget, as it reduces the amount of precipitation available for SWC. 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 mechanical function of the storage space of vegetation structure (Wilm, 1957). Forests with dense crowns and large leaf areas have higher interception losses (IPCC, 2000), cloud forests being the exception. Interception losses are 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 coefficients, widely available in the literature for the six vegetation classes, namely Tree, Shrubs, Pasture, Grass, Crop and Bare Land (Hamilton and Rowe, 1949; Young et al., 1984; Thurow et al., 1987; Farrington and Bartle, 1991; Calder, 1992; Tate, 1996; Le Maitre et al., 1999; Schroth et al., 1999), with the estimated occurrence of that vegetation class within a land use type.

For each month Eprec_m is calculated as:

$$\text{Eprec}_m = \text{Gprec} - \text{Int} \quad (8)$$

where Int is equal to:

$$\text{Int} = (\text{Gprec} \times K_{\text{int}}) \quad (9)$$

Therefore:

$$\text{Eprec}_m = \text{Gprec} - (\text{Gprec} \times K_{\text{int}}) = \text{Gprec} \times (1 - K_{\text{int}}) \quad (10)$$

The AET and Int components of the model are combined 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').

2.6. 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 proposed for CDM-AR (Zomer et al., 2006). These four sites, two sites in Ecuador and two in Bolivia, represent a range of biophysical conditions and project scenarios (Table 2), including production of eucalyptus, pine, restoration of native *Polylepis besserli* woodland, and a mixed agroforestry of native tropical timber species. Changes in water cycles were modeled as a consequence of a projected land use change to a specific proposed CDM-AR scenario for that site. Using both global and locally available data, the proposed CDM-AR project scenario for each site was compared with the current existing land use, at a resolution of 30 m. Current and historical tree canopy cover was estimated from Landsat TM imagery, and elevation was derived from SRTM 90 m DEM data (downloaded from CGIAR-CSI STRM 90m Database: http://srtm.cgiar.csi.org). Growth characteristics for specific species, used to optimize the spatial distribution of CDM-AR species were obtained from literature and expert knowledge, where available.

3. Results and discussion

3.1. Global 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 within the landscape (surface and subsurface) 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

Table 2
Socio-ecological characteristics and project scenarios for the four case study sites (ENCOFOR 2004)

CDM-AR case study site	Ecological zone	Elevation (m)	Precipitation (mm/yr)	Temperature (°C)	Population	Project scheme
Tunari National Park, 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

Author's personal copy

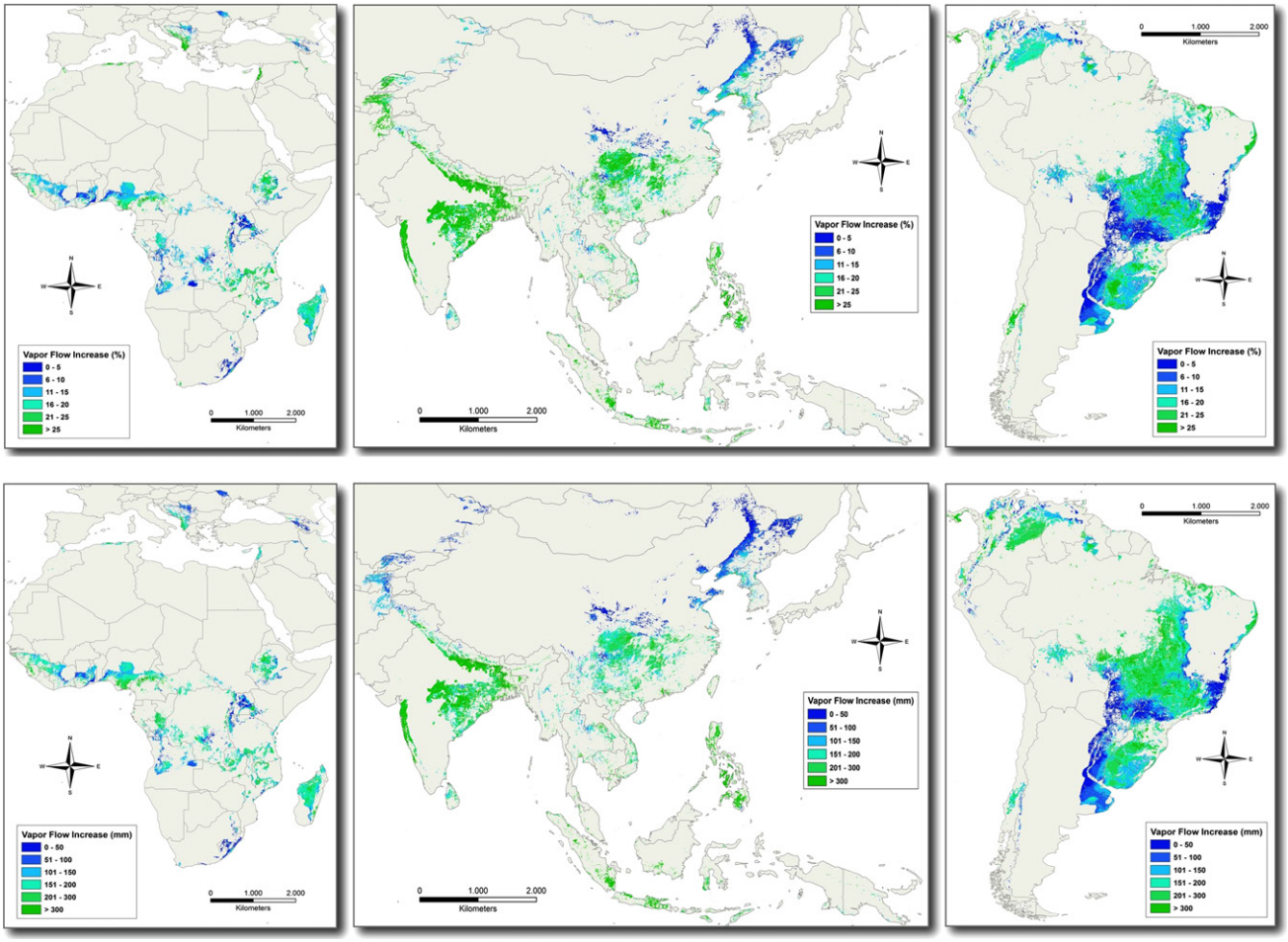


Fig. 3. Increases in vapor flow resulting from land use change to CDM-AR, are given both in absolute terms (mm), and as the percentage increase (%) from existing land use. Vapor flow includes both the AET and Int components of the water balance model.

and mapped in this analysis. Together they indicate that large areas deemed suitable for CDM-AR would exhibit significant increases in vapor flow (Fig. 3) and/or substantial decreases in runoff (Fig. 4). This is particularly evident in drier areas, the semi-arid tropics, and in conversion to trees from grasslands and subsistence agriculture. In these semi-arid areas, river flows may account for only a small percentage of rainfall (5–10%), therefore conversion to forestry can have a big difference on river flow.

Significant variation amongst biomes and bioclimatic zones is evident. In particular, AI proved to be a good indicator of the percent decrease in runoff the can be expected with afforestation (Fig. 5). Almost 20% (144 Mha) of all suitable land showed little or no impact on runoff with another 28% (210 Mha) showing only moderate impact (Table 3). Taken together 50% of all suitable land showed a decrease in runoff of less than 60% (Fig. 6). About 27% of the available area (200 Mha) is in the highest impact class exhibiting an 80–100% decrease in runoff. Altogether, almost 60% showed a decrease of less than 200 mm and only slightly more than 13% showed a decrease of more than 300 mm (Table 4).

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, as only 2% of the available land would be needed to satisfy the 1% cap on CDM-AR (Zomer et al., 2008), 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, could have potential impacts on the regional hydrological cycle.

3.2. Local scale water use impact of CDM-AR

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

Author's personal copy

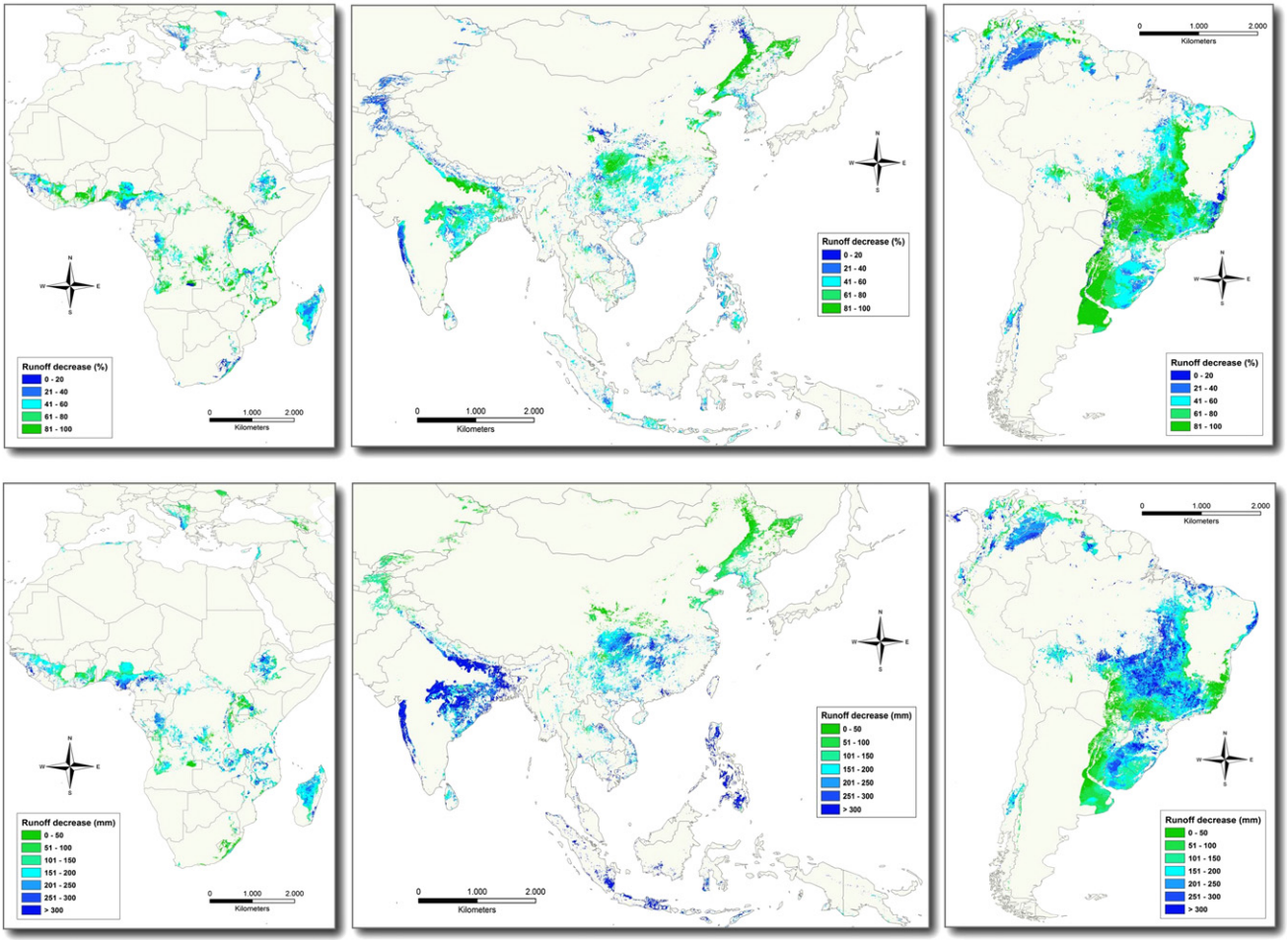


Fig. 4. Decreases in runoff resulting from land use change to CDM-AR, are given both as the percentage decrease (%) from existing land use, and in absolute terms (mm).

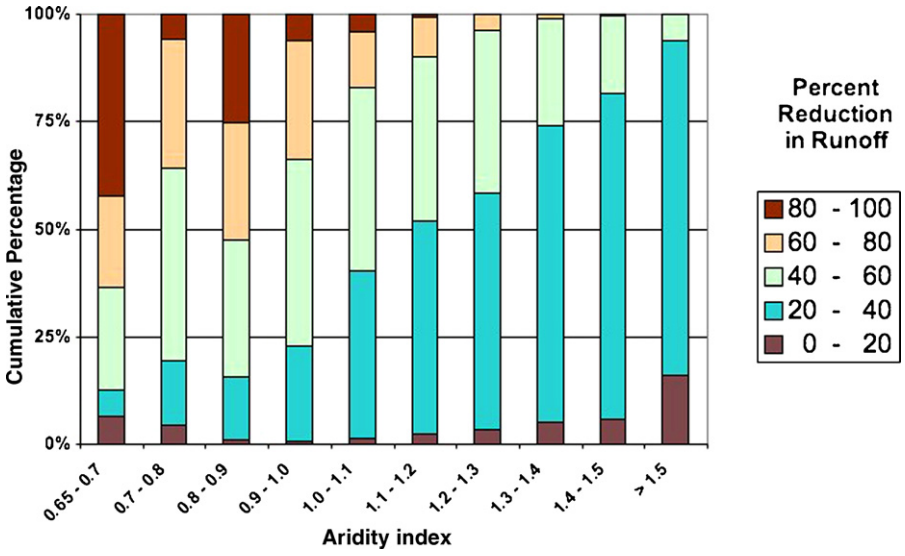


Fig. 5. The percent reduction in runoff by Aridity Index (AI).

Author's personal copy

Table 3
Percent decrease in runoff (%) with land use change to CDM-AR on suitable land, regionally and globally

Percent decrease in runoff (%)					
	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
South-east Asia	11	48	94	87	119
Global	28	116	210	183	200

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 (Dingman, 1993). All four sites showed a marked reduction in runoff, with both on-site and off-site implications (Table 5). On the humid lowland tropical Amazon site in Chapare, Bolivia (Fig. 7), 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 (Fig. 8) showed significant decrease (28%) 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

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

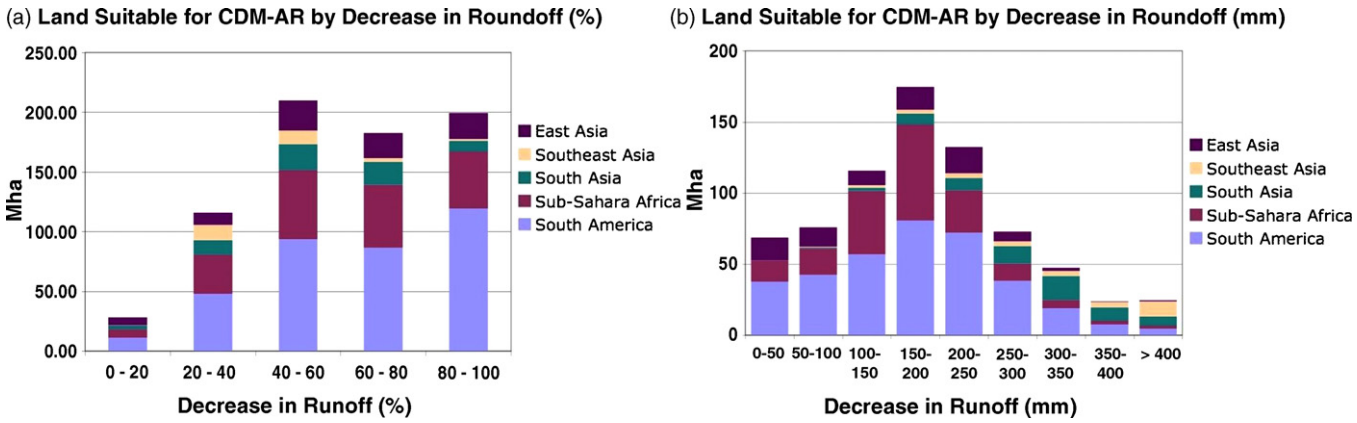


Fig. 6. (a) Relative percentage decrease in runoff (%), by regions, with land use change to CDM-AR; (b) absolute decrease in runoff (mm), by regions, with land use change to CDM-AR.

Table 5
Results of water balance model at local scale for four case studies

CDM-AR case study site	Project area (ha)	CDM-AR area (ha)	Precipitation (mm/yr)	Aridity Index (mean AI)	Vapor flow (% increase)	Runoff (% decrease)	SWC (% decrease)
Tunari National Park, 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

Vapor flow is given here as the sum of AET and Int, in order to represent total ET, and is presented as the percent increase resulting from land use change to CDM-AR. Runoff and SWC are given as the percent decrease resulting from land use change to CDM-AR.

Author's personal copy

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, which this study suggests are the likely outcomes of reforestation efforts 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 (Fig. 9), the water implication of afforestation with pine trees is a controversial issue (Farley et al., 2004). However, this project is designed to restore and stabilize the sandy soils

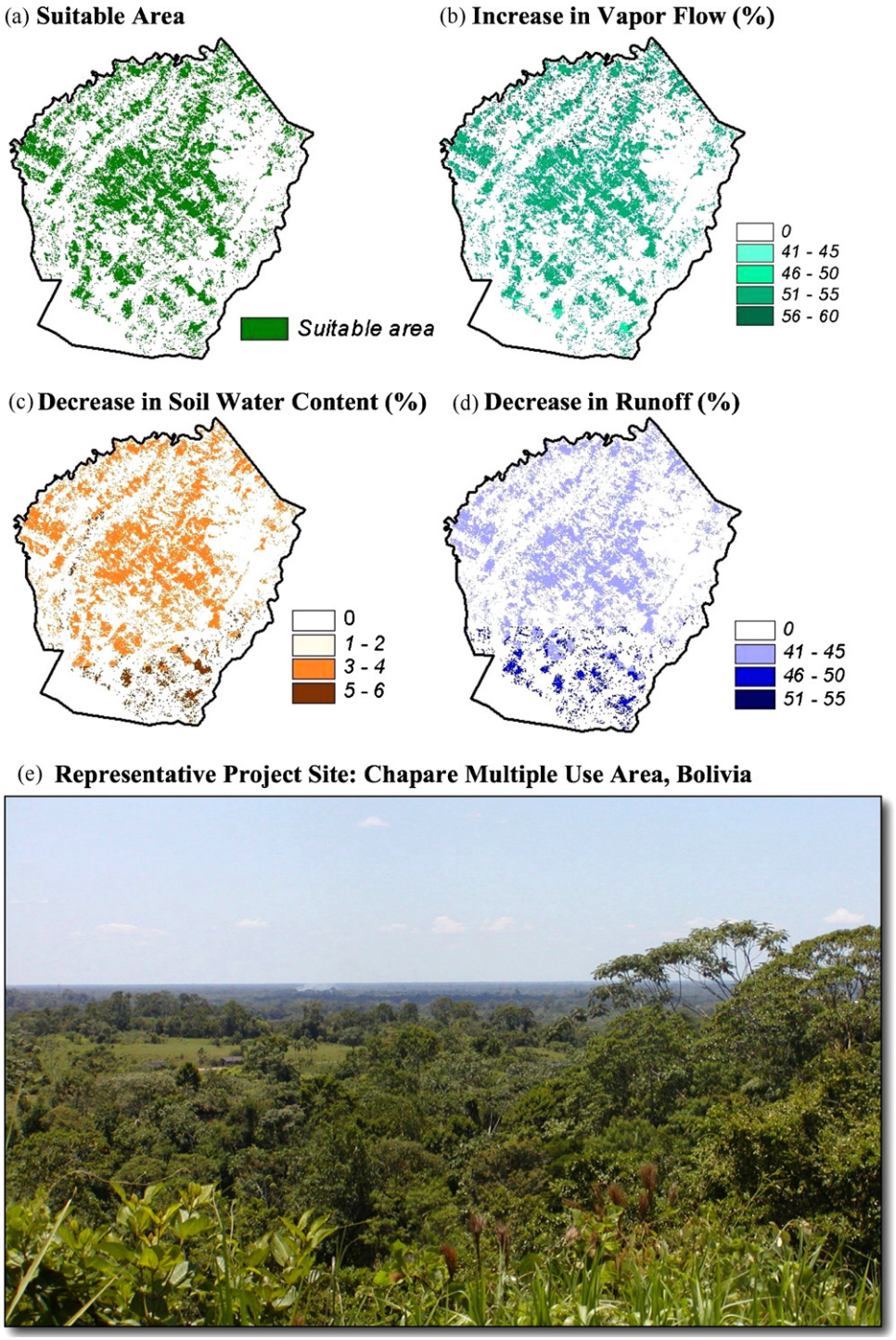


Fig. 7. Chapare case study: (a) CDM-AR suitable land; (b) increase in vapor flow with land use change to CDM-AR; (c) decrease in SWC with land use change to CDM-AR; (d) decrease in runoff with land use change to CDM-AR; (e) representative view of the site.

Author's personal copy

of this region which have degraded in many areas into sand dunes. In addition to a decrease in runoff (54%), there also appears to be a significant impact on soil water content (decrease of 32%), indicating a likelihood of decreasing water table levels over time. However, there is likely to be a decrease in sediment loss by water and wind erosion. Increases in AET and total vapor flows are relatively small, since this system is already water limited under the current land use. The modeling results in this case, predict the commonly expected consequences of afforestation projects using fast-growing conifers: 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 (Fig. 10) was

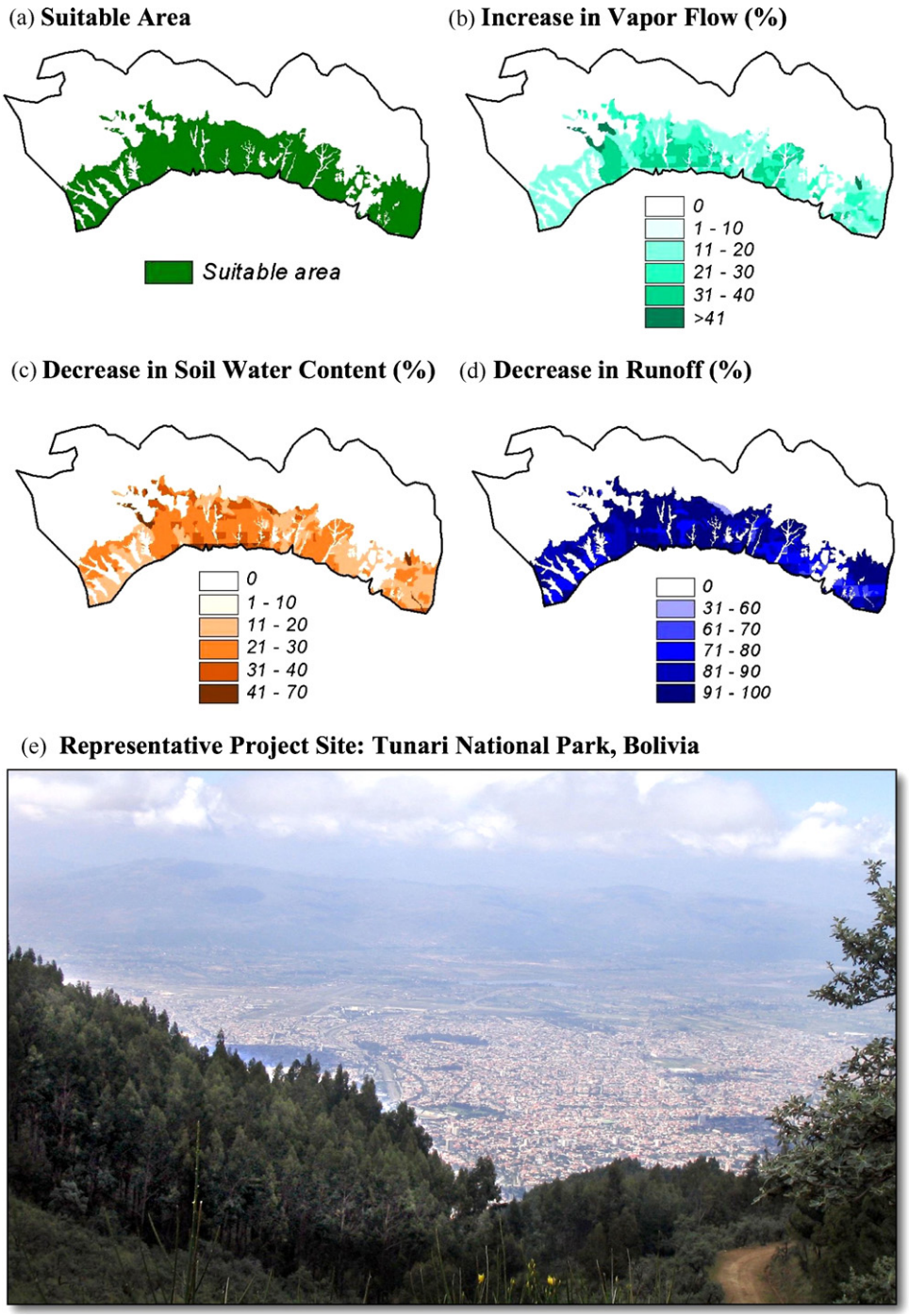


Fig. 8. Tunari case study: (a) CDM-AR suitable land; (b) increase in vapor flow with land use change to CDM-AR; (c) decrease in SWC with land use change to CDM-AR; (d) decrease in runoff with land use change to CDM-AR; (e) representative view of the site.

Author's personal copy

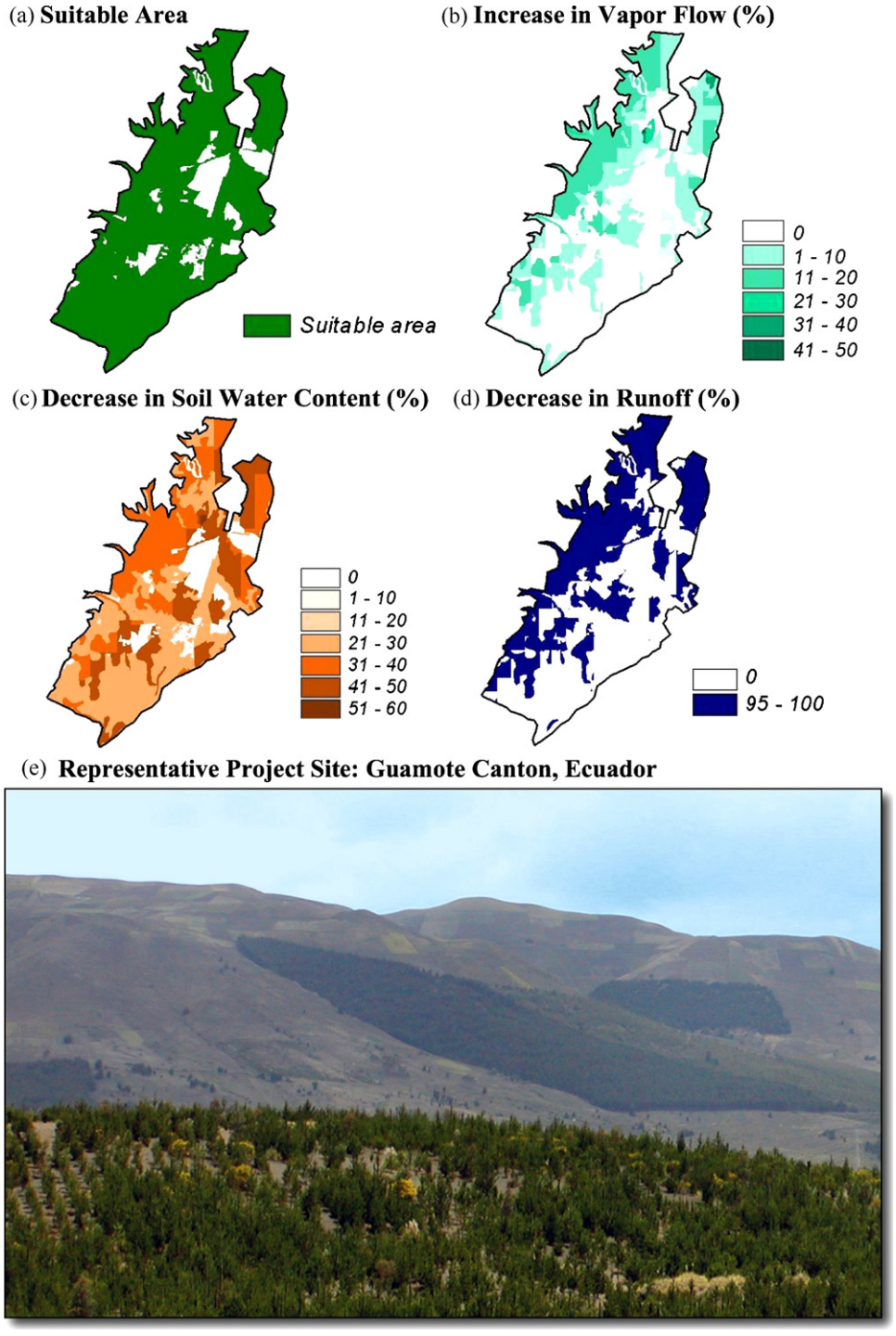


Fig. 9. Guamote case study: (a) CDM-AR suitable land; (b) increase in vapor flow with land use change to CDM-AR; (c) decrease in SWC with land use change to CDM-AR; (d) decrease in runoff with land use change to CDM-AR; (e) representative view of the site.

relatively large (47%). However, the generally higher level of precipitation and the site's downstream location within the catchment minimized the importance of the decrease in runoff.

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

Author's personal copy

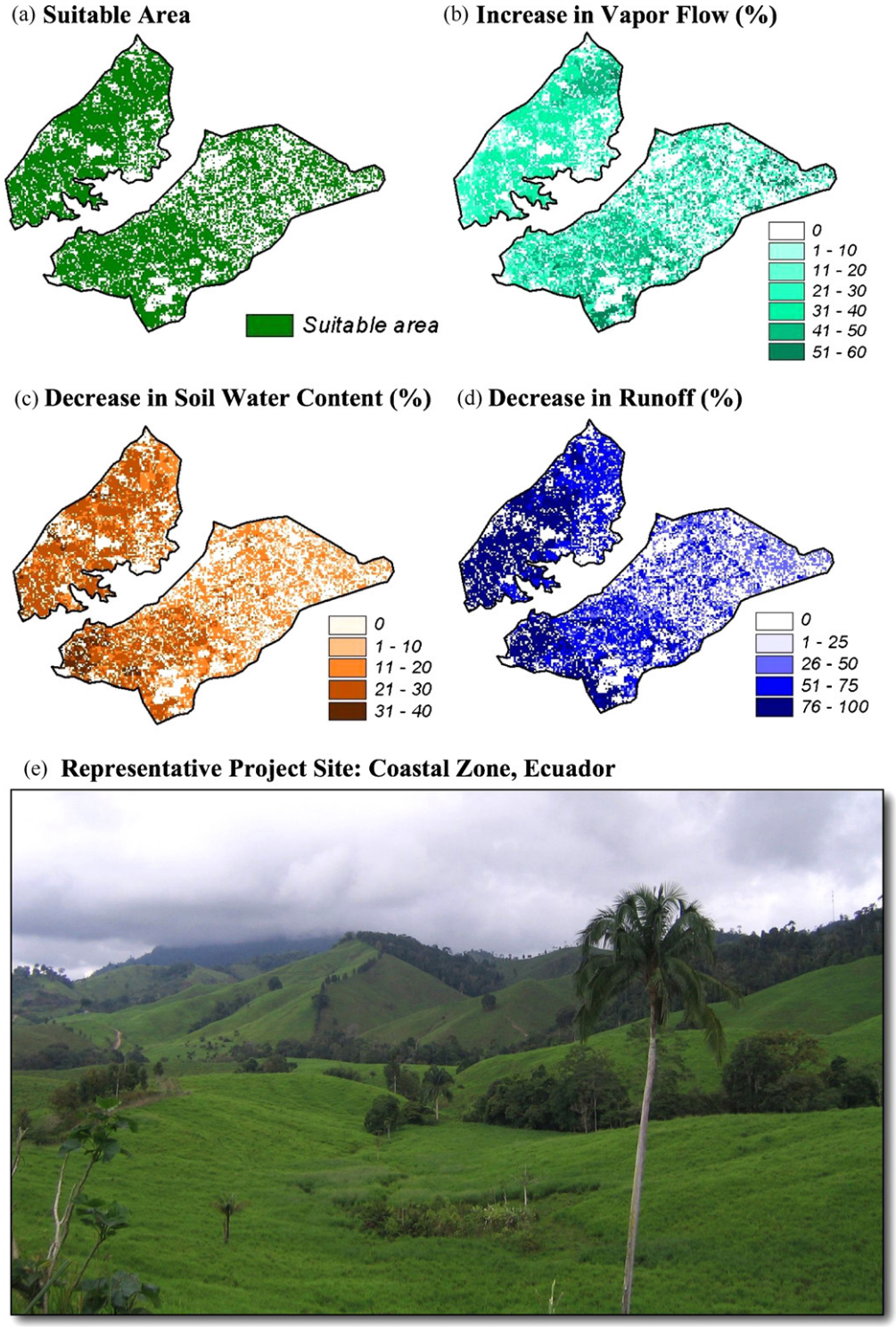


Fig. 10. Coastal Ecuador case study: (a) CDM-AR suitable land; (b) increase in vapor flow with land use change to CDM-AR; (c) decrease in SWC with land use change to CDM-AR; (d) decrease in runoff with land use change to CDM-AR; (e) representative view of the site.

4. Conclusion

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. In this analysis we highlighted the 'hidden' water dimension associated with climate change mitigation efforts based on afforestation/reforestation, and we speculate that this dimension can be

Author's personal copy

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.

Impacts of CDM-AR on the hydrological cycle are not evident at regional or global scale under current rules because the land area that is potentially affected is not significant. If the cap on CDM-AR were raised to allow for a substantially greater offset of carbon emission through sink projects, it will become increasingly important to consider implications on regional water resources. This important hydrologic dimension of CDM-AR should be formally articulated and taken into account environmental impact studies required by the CDM-AR guidelines, especially when addressing issues of sustainability, local communities, and food security.

We already know that afforestation of upland catchments with fast growing plantations can have significant impact on in situ water use, with consequent impacts on water availability downstream, and this was confirmed in one of our case studies. Generally, 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 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. However, in this analysis these effects were not compared with the various climate change scenarios, which predict significant future changes in precipitation and variability of rainfall across the globe. This points to even more basic and functional changes in the hydrological cycle already underway from climate change. For example, 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 use efficient.

Our hydrological analysis shows the potential for significant impacts on local hydrologic cycles through CDM-AR activities. The variation in the case studies also points to the possibility of positive impacts, and thus the potential for synergies in environmental management and climate change mitigation. On a national and local basis, the selection of CDM-AR sites can take into consideration the specific hydrologic and socio-ecological aspects of projects, in order 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.

Acknowledgements

The authors would like to acknowledge the support of the International Water Management Institute (IWMI), and the World Agroforestry Center. Local case studies were completed with research support provided by a grant from the European Union/EuropeAid (B7-6200/2002/069-203/TPS) within the framework of the ENCOFOR Project (see http://www.joanneum.at/encofor). We would like to thank the institutions responsible for leading the work of the ENCOFOR project in the participating countries for facilitating the data collection: in Bolivia, Fundación Centro Técnico Forestal (CETEFOR), and in Ecuador, Programa Face de Forestación (PROFAFOR). We would personally like to thank the ENCOFOR Project team: Igino Emmer and Bart Muys for coordination and project management; the ENCOFOR country partners in Ecuador, Bolivia, and Uganda: Luis Fernando, Anko Stilma, Timm Tennigkeit; and our colleagues from the Joanneum Institute: Bernhard Schlamadinger, Hannes Schwaiger, and Neil Bird for their valuable contributions to this work. Many thanks to Vladimir Smakhtin of IWMI and Bart Muys of K.U. Leuven for valuable advice, reviews and comments on previous versions of the manuscript. Much appreciation goes to the IWMI RS/GIS Team—Sadir Mohideen, Anjitha Senarath, Li Yuanjie, and Aminul Islam.

References

Alcamo, J., Doll, P., Kaspar, F., Siebert, S., 1997. Global Change and Global Scenarios of Water Use and Availability: An Application of WaterGAP 1.0. CESR (Center for Environmental Systems Research), University of Kassel, Kassel, Germany.

Alcamo, J., Henrichs, T., Rosch, T., 2000. World water in 2025: global modeling and scenario analysis. In: Rijsberman, F.R. (Ed.), World Water Scenarios Analyses. World Water Council, Marseille.

Allen, R.G., Pereira, L.S., Raes, D., Smith, M., 1998. Crop evapotranspiration—guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. FAO (Food and Agriculture Organization of the United Nations), Rome.

Andréassian, V., 2004. Waters and forests: from historical controversy to scientific debate. J. Hydrol. 291, 1–27.

Aylward, B., Echeverria, J., Gonzales, A.F., Porras, I., Allen, K., Mejias, R., 1998. Economic incentives for watershed protection: a case study of Lake Arenal, Costa Rica. Final Report to the Government of the Netherlands under the Program of Collaborative Research in the Economics of Environment and Development (CREED). IIED (International Institute for Environment and Development), TSC (Tropical Science Center) and the International Center for Economic Policy, National University at Heredia (CINPE), London, p. 140.

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

Author's personal copy

Bormann, F.H., Likens, G.E., 1995. The Biogeochemistry of a Forested Ecosystem, second ed. Springer Verlag, New York, p. 160.

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

Bruijnzeel, L.A., 2004. Hydrological functions of tropical forests: not seeing the soil for the trees? Agric. Ecosyst. Environ. 104 (1), 185–228.

Calder, I.R., 1992. Water use in eucalypts—a review. In: Calder, I.R., Hall, R.L., Adlard, P.G. (Eds.), Growth and Water Use of Forest Plantations. J. Wiley, New York, pp. 167–179.

Calder, I.R., 2000. Land use impacts on water resources. Land-Water Linkages in Rural Watersheds Electronic Workshop, Background Paper No. 1, September 18–October 27. FAO.

CIFOR, FAO, 2005. Forests and floods: drowning in fiction or thriving on facts? Forest Perspectives. Center for International Forestry Research, No. 2. 38 pp.

Costello, L.R., Jones, K.S., 2000. Water Use Classification of Landscape Species (WUCOLS III). A Guide to Estimating Irrigation Water Needs of Landscape Plantings in California. Department of Water Resources, Sacramento, California.

Dingman, S.L., 1993. Physical Hydrology. Prentice Hall, New Jersey, USA.

Droogers, P., Allen, R.G., 2002. Estimating reference evapotranspiration under inaccurate data conditions. Irrig. Drain. Syst. 16 (1), 33–45.

Dyck, S., 1983. Overview on the present status of the concepts of water balance models. In: Proceedings of the Hamburg Workshop New Approaches in Water Balance Computations. Int. Assoc. of Hydro. Sci. Publ. No. 148, IAHS, Wallinford, UK, pp. 3–19.

Falkenmark, M., 1995. Land and water integration and river basin management. In: FAO Land and Water Bulletin Number 1, FAO, Rome, Italy, pp. 15–16.

Falkenmark, M., Lannerstad, M., 2004. Consumptive water use to feed humanity—curing a blind spot. Hydrol. Earth Syst. Sci. Discuss. 1, 7–40.

FAO (Food and Agriculture Organization of the United Nations), 1995. Digital Soil Map of the World (DSMW): based on the FAO/UNESCO Soil Map of the World, Original Scale 1:5 000 000. FAO-AGL (Land and Water Development Division), Rome.

FAO, 2001a. FAOCLIM—World-Wide Agroclimatic Data. Version 2. FAO–SDRN (Environment and Natural Resources Service), Rome.

FAO, 2001b. Crops and Drops: Making the Best Use of Water for Agriculture. FAO (Food and Agriculture Organization of the United Nations), Rome.

FAO, 2003a. Agriculture, Food and Water: A Contribution to the "World Water Development Report". FAO (Food and Agriculture Organization of the United Nations), Rome.

FAO, 2003b. Unlocking the Water Potential of Agriculture. FAO (Food and Agriculture Organization of the United Nations), Rome.

Farley, K.A., Kelly, E.F., Hofstede, R.G.M., 2004. Soil organic carbon and water retention after conversion of grasslands to pine plantations in the Ecuadorian Andes. Ecosystems 7 (7), 729–739.

Farrington, P., Bartle, G.A., 1991. Recharge beneath a *Banksia* woodland and a *Pinus pinaster* plantation on coastal deep sands in south Western Australia. Forest Ecol. Manag. 40, 101–118.

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

Gordon, L.J., Steffen, W., Jonsson, B.F., Folke, C., Falkenmark, M., Johannessen, A., 2005. Human modification of global water vapor flows from the land surface. PNAS Proc. Natl. Acad. Sci. U.S.A. 102, 7612–7617.

Hamilton, E.L., Rowe, P.B., 1949. Rainfall Interception by Chaparral in California. Division of Forestry, Sacramento, California.

Hargreaves, G.H., 1994. Defining and using reference evapotranspiration. J. Irrig. Drain. Eng. ASCE 120 (6), 1132–1139.

Hargreaves, G.H., Allen, R.G., 2003. History and evaluation of Hargreaves evapotranspiration equation. J. Irrig. Drain. Eng. ASCE 129 (1), 53–63.

Hargreaves, G.L., Hargreaves, G.H., Riley, J.P., 1985. Irrigation water requirements for Senegal River Basin. J. Irrig. Drain. Eng. ASCE 111 (3), 265–275.

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

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., 2004. The WorldClim interpolated global terrestrial climate surfaces. Version 1.3. Downloaded at: http://biogeo.berkeley.edu/worldclim/worldclim.htm.

Holland, H.D., 1978. The Chemistry of the Atmosphere and Oceans. Wiley, New York.

IPCC, 2000. Intergovernmental panel on climate change, special report on land use, land-use change and forestry. A Special Report of the Intergovernmental Panel on Climate Change. Approved at IPCC Plenary XVI (Montreal, 1–8 May, 2000). IPCC Secretariat, c/o World Meteorological Organization, Geneva, Switzerland (at http://www.ipcc.ch/).

IWMI, 2000. World water supply and demand in 2025. In: Rijsberman, F.R. (Ed.), World Water Scenario Analyses. World Water Council, Marseille.

Jackson, R.B., Jobbágy, E.G., Avissar, R., Roy, S.B., Barrett, D.J., Cook, C.W., Farley, K.A., le Maitre, D.C., McCarl, B.A., Murray, B.C., 2005. Trading water for carbon with biological carbon sequestration. Science 310 (5756), 1944–1947.

Jensen, M.E., Burman, R.D., Allen, R.G., 1990. Evapotranspiration and irrigation water requirements. ASCE Manuals and Reports on Engineering Practice. American Society of Civil Engineers, New York.

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

Le Maitre, D.C., Scott, D.F., Colvin, C., 1999. A review of information on interactions between vegetation and groundwater. Water SA 25 (2), 137–152.

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

Matthews, D., 2006. The water cycle freshens up. Nature 439, 793–794.

NIMA (National Imagery and Mapping Agency), 1997. VectorMap (VMAP) Level 1. Department of DefenseNational GeoSpatial Agency, US.

Raskin, P., Gleick, P., Kirshen, P., Pontius, G., Strzepek, K., 1997. Water Futures: Assessment of Long-Range Patterns and Prospects. Stockholm Environment Institute, Stockholm.

Rijsberman, F., Bossio, D.A., Noble, A.D., 2006. The impact of land degradation and improved land management on water productivity. In: International Conference of Soil, Water and Environmental Quality—Issues and Strategies, New Delhi, India, January 28–February 1, 2005.

Rockstrom, J., Gordon, L., Folke, C., Falkenmark, M., Engwall, M., 1999. Linkages among water vapor flows, food production, and terrestrial ecosystems services. Conserv. Ecol. 3 (2), 5.

Schenk, H.J., Jackson, R.B., 2002. The global biogeography of roots. Ecol. Monogr. 72, 311–328.

Schroth, G., da Silva, L.F., Wolf, M.A., Teixeira, W.G., Zech, W., 1999. Distribution of throughfall and stemflow in multi-strata agroforestry, perennial monoculture, fallow and primary forest in central Amazonia, Brazil. Hydrol. Process. 13, 1423–1436.

Schulze, E.D., 1982. Plant life forms and their carbon, water and nutrient relations. In: Lange, O.L., Osmond, C.B., Ziegler, V. (Eds.), Physiological Plant Ecology II. Water Relations and Carbon Assimilation. Springer-Verlag, Berlin, pp. 615–676.

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

Shiklomanov, I.A., 1991. The world's water resources. In: Proc. International Symposium to Commemorate 25 Years of the IHP. UNESCO/IHP, Paris, pp. 93–126.

Shiklomanov, I.A., 1998. World water resources: An appraisal for the 21st century. IHP Report. UNESCO, Paris.

Author's personal copy

Smakhtin, V., Revenga, C., Doll, P., 2004. Taking into account environmental water requirements in global-scale water resources assessments. Comprehensive Asessment of Water Management in Agriculture Research Report 2. International Water Management Institute, Colombo, Sri Lanka.

Swank, W.T., Douglass, N.H., 1974. Streamflow greatly reduced by converting deciduous hardwood stands to pine. Science 185, 857–859.

Tate, K.W., 1996. Interception on rangeland watersheds. Fact Sheet No. 36. University of California. Cooperative Extension and USDA Natural Resources Conservation Service, Rangeland Watershed Program.

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

Thornthwaite, C., Mather, J., 1955. The water balance. Publ. Climatol. 8 (1), 1–104.

Thurow, T.L., Blackburn, W.H., Taylor, C.A., 1987. Rainfall interception by midgrass, shortgrass and live oak mottes. J. Range Manag. 40, 455–460.

U.S. Bureau of Reclamation, 2005. Agrimet Data System.

UNFCCC (United Nations Framework Convention on Climate Change), 2002a. Report of the Conference of the Parties on its Seventh Session, held in Marrakech from October 29–November 10, 2001. Addendum Part Two: Action Taken by the Conference of the Parties Volume I (FCCC/CP/2001/13/Add. 1). United Nations Framework Convention on Climate Change Secretariat, Bonn, Germany.

UNFCCC (United Nations Framework Convention on Climate Change), 2002b. Report of the Conference of the Parties on its Seventh Session, held in Marrakech from October 29–November 10, 2001. Addendum Part Two: Action Taken by the Conference of the Parties Volume II (FCCC/CP/2001/13/Add. 1). United Nations Framework Convention on Climate Change Secretariat, Bonn, Germany.

Verchot, L.V., Zomer, R.J., van Straaten, O., Muys, B., 2007. Implications of country-level decisions on the specification of crown cover in the definition of forests for land area eligible for afforestation and reforestation activities in the CDM. Climate Change 81 (3–4), 415–430.

Vincent, J.R., 1995. Timber trade, economics, and tropical forest management. In: Ecology, Conservation and Management of Southeast Asia Rainforests, Yale University Press, New Haven, CN, USA, pp. 241–261.

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

Wallace, J.S., 2000. Increasing agricultural water efficiency to meet future food production. Agric. Ecosyst. Environ. 82, 105–119.

Wallace, J.S., Gregory, P.J., 2002. Water resources and their use in food production. Aquat. Sci. 64, 363–375.

WHO, 2006. World Health Organization. Water Sanitation and Health Website: http://www.who.int/water_sanitation_health/hygiene/en/.

Wilm, H.G., 1957. The influence of forest vegetation on water and soil. Unasylva 11 (4).

Young, J.A., Evans, R.A., Easi, D.A., 1984. Stemflow on western juniper (*Juniprus occidentalis*) trees. Weed Sci. 32, 320–327.

Zomer, R.J., Trabucco, A., van Straaten, O., Bossio, D.A., 2006. Carbon, land and water: A global analysis of the hydrologic dimensions of climate change mitigation through afforestation/reforestation. IWMI Research Report 101. International Water Management Institute, Colombo, Sri Lanka. p. 48.

Zomer, R.J., Trabucco, A., Bossio, D.A., Vercot, L.V., 2008. Climate change mitigation: a spatial analysis of global land suitability for clean development mechanism afforestation and reforestation. Agric. Ecosyst. Environ. 126 (1–2), 67–80.