An alternative approach for quantifying climate regulation by ecosystems

Paul C West[1,2*], Gemma T Narisma[1,3], Carol C Barford[1], Christopher J Kucharik[1,4], and Jonathan A Foley[5]

Ecosystems provide multiple benefits to people, including climate regulation. Previous efforts to quantify this ecosystem service have been either largely conceptual or based on complex atmospheric models. Here, we review previous research on this topic and propose a new and simple analytical approach for estimating the physical regulation of climate by ecosystems. The proposed metric estimates how land-cover change affects the loading of heat and moisture into the atmosphere, while also accounting for the relative contribution of wind-transported heat and moisture. Although feedback dynamics between land, atmosphere, and oceans are not modeled, the metric compares well with previous studies for several regions. We find that ecosystems have the strongest influence on surface climatic conditions in the boreal and tropical regions, where temperature and moisture changes could substantially offset or magnify greenhouse-forced changes. This approach can be extended to estimate the effects of changing land cover on local, physical climate processes that are relevant to society.

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Ecological research on the benefits that people derive from ecosystems has greatly increased over the past decade. These benefits, often called "ecosystem goods and services", range from basic provisions like food and water, to the regulation of water quality and climate (Costanza *et al*. 1997; Daily 1997; MA 2005). Climate regulation – which we define here as the influence of ecosystems on near-surface climatic conditions, such as air temperature and moisture – is an important ecosystem service that has been identified in many studies.

Previous efforts to quantify climate regulation by ecosystems have emphasized *biogeochemical regulation*, a process in which ecosystems affect global concentrations of CO_2 and other greenhouse gases (GHGs) by removing them from the atmosphere and storing them in plant biomass or soil organic matter. However, removal and net storage of CO_2 (or other GHGs) is not the only way ecosystems can regulate climate. They also play a crucial role in modulating the balances of energy, water, and physical momentum across the lower atmosphere, and exert a considerable influence on regional climates (Pielke *et al*. 2002; Foley *et al*. 2003; Meir *et al*. 2006; Chapin *et al*. 2008). These processes constitute *biophysical regulation* of climate.

In a nutshell:

- Ecosystems regulate global climate through both biogeochemical and biophysical processes, although most studies have only focused on the biogeochemical processes linked to CO_2
- Effects of land-use change on surface energy and water balance can outweigh the influence of increased CO_2 on regional climate
- Estimating the relative influence of changing land cover – versus that of large-scale atmospheric circulation – on local heat and moisture budgets allows us to estimate physical climate regulation by ecosystems
- This simple, physically based approach gives results similar to those produced by complex, coupled climate models

[1]*Center for Sustainability and the Global Environment (SAGE), University of Wisconsin-Madison, Madison, WI; current address: Institute on the Environment, University of Minnesota, St Paul, MN;* [2]*The Nature Conservancy, Madison, WI* [*]*(pcwest@umn.edu);* [3]*Ateneo de Manila University, Loyola Heights, Quezon City, Philippines;* [4]*Department of Agronomy, University of Wisconsin-Madison, Madison, WI;* [5]*Institute on the Environment, University of Minnesota, St Paul, MN*

Quantifying this biophysical regulation of climate by ecosystems (especially through effects on atmospheric heat and moisture) has largely eluded ecologists. Current approaches for quantifying this ecosystem service are at two ends of a spectrum – largely conceptual approaches at one end and highly complex atmospheric General Circulation Models (GCMs) at the other. Unfortunately, conceptual approaches are of limited use to resource managers and policy makers, and few non-meteorologists have access (or the expertise) to run and interpret high-end GCM systems. A simple, physically based metric of ecosystem climate regulation – one that can be easily interpreted – is greatly needed.

Why do we need a climate regulation index?

Land-use and land-cover change are major drivers of global ecological change and strongly influence regional climate. Between 30–40% of the natural vegetation on the Earth's surface has been converted to pastures and croplands (Foley *et al*. 2005), and this area is currently expanding by approximately 13 million ha per year (FAO 2002).

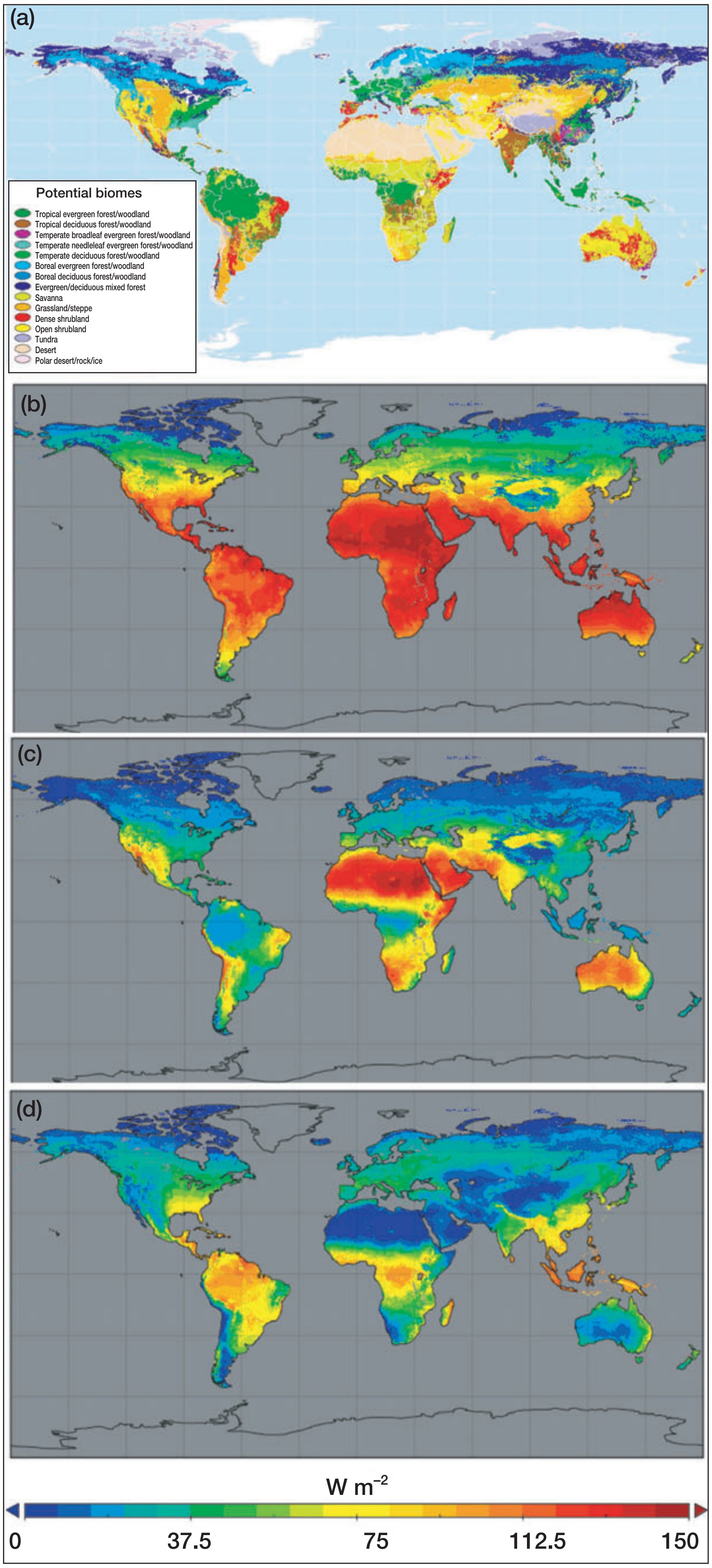

***Figure 1.** Vegetation partitions absorbed solar radiation into energy fluxes that affect air temperature and moisture. This figure shows baseline conditions of energy fluxes assuming potential natural vegetation (a) and that net radiation absorbed by the Earth's surface (b) is released either as a warming process in the form of sensible heat (c) or as a cooling process in the form of latent heat (d). (Distribution of potential natural vegetation data from Ramankutty and Foley 1999.)*

The effects of this changing landscape on climate could be very important at regional and global scales (Foley *et al.* 2003), creating new challenges for biodiversity conservation and management of critical environmental systems. How will increasing land use affect regional climate? Could expanding managed lands change the climate enough to alter which crops are suitable for a particular region? Could changes in regional land-cover patterns, and associated changes in regional climate, impede our ability to conserve small fragments of biodiversity in isolated reserves?

Our aim is to develop a simple climate regulation index that quickly produces approximations of biophysical regulation of climate by terrestrial ecosystems. Here, we first review the mechanisms of biophysical regulation of climate by ecosystems. We then use observed climate data and a simple land-surface model to estimate potential changes to energy and water balances resulting from land-use change. Finally, these results are compared with results from other modeling approaches that use land-surface models coupled with GCMs.

Biophysical climate regulation

Climate regulation by ecosystems goes far beyond sequestering carbon (Pielke *et al.* 2002; Foley *et al.* 2003; Marland *et al.* 2003; Meir *et al.* 2006). Ecosystems also regulate the climate through biophysical processes that mediate energy and water balances at the land surface. In an equilibrium state, the incoming solar radiation is balanced by energy released from the land surface. The reflectivity (ie albedo) of the land surface determines the amount of solar radiation that the land absorbs. This absorbed radiation is primarily released as

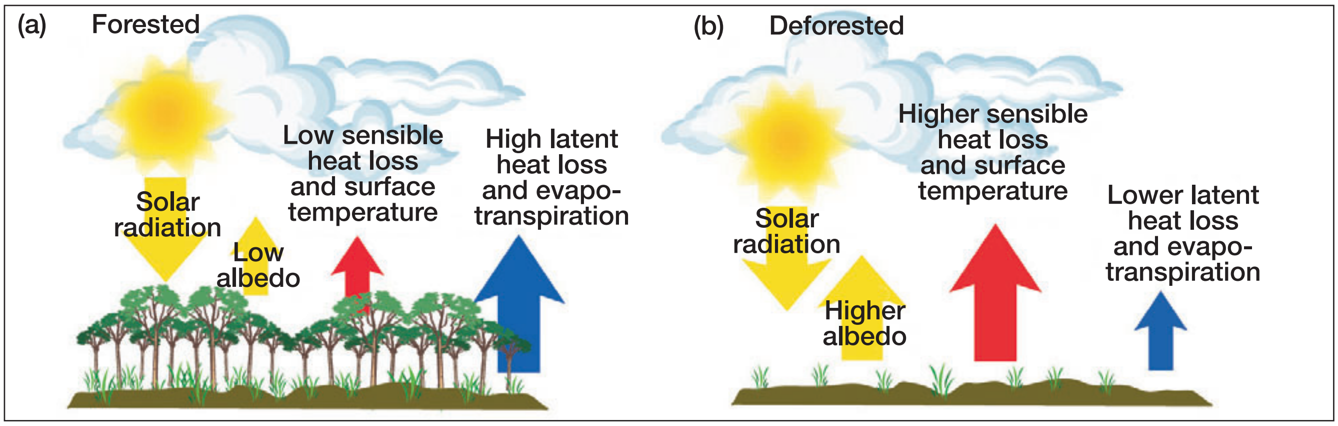

Figure 2. *Effects of land-cover change on climate regulation in tropical rainforests. Although less solar radiation is absorbed in deforested areas, a greater proportion of the net radiation is released as sensible heat, resulting in a warmer and drier climate near the surface. (Figure adapted from Foley* et al. *2003.)*

infrared radiation, sensible heat (energy that is transferred from the land surface to the air), and latent heat. Sensible heat has a warming effect on the near-surface climate and can be measured with a thermometer. In contrast, latent heat is the energy absorbed during the conversion of water from one state to another (eg melting, evaporation, and evapotranspiration).

Ecosystems actively partition the net radiation, influencing the proportion that is returned as latent heat versus sensible heat fluxes (Figure 1). For example, dry regions with sparse vegetation release relatively high amounts of sensible heat, which warms the air near the surface. However, in regions with wet climates and dense vegetation cover, the abundance of liquid water at the surface requires more energy to supply the latent heat of vaporization. This reduces the net radiation available as sensible heat and creates a net cooling effect on the air near the land surface. Together, these latent and sensible heat fluxes provide the "fuel" for the near-surface mixing zone called the planetary boundary layer.

Thus, land cover strongly influences regional air temperature and moisture (Bonan 2002; Foley *et al.* 2003; Meir *et al.* 2006; Chapin *et al.* 2008; Figure 2). Typically, the effects of land-cover change on local and regional atmospheric heat and moisture outweigh the projected change in air temperature associated with increasing CO_2 in the atmosphere (Costa and Foley 2000; Pielke *et al.* 2002; Marland *et al.* 2003; Feddema *et al.* 2005), at least at the regional scale. For example, changes in surface energy and water balances from large-scale deforestation of the Amazon rainforest have a stronger influence on the climate of the Amazon Basin than a projected global doubling of CO_2 (Costa and Foley 2000).

The influence of local land cover on local climate varies among ecosystems, depending on the amount of vegetation cover, leaf area index, rooting depth, albedo, and physiological properties of both the previous and the converted landscape. For example, removing dense forest vegetation has more pronounced effects on the local climate than removing sparse vegetation, because forested areas generally have a lower albedo, higher vegetative cover and leaf area index, and higher maximum transpiration rates than most shrub, grass, or desert ecosystems (Bonan 2002).

Quantifying ecosystem regulation of atmospheric heat and moisture

Previous efforts to quantify the biophysical regulation of climate by ecosystems have largely focused on regional analyses, using GCMs that include land-surface models coupled with atmospheric circulation models (hereafter referred to as "coupled GCMs"). These regional-scale analyses have focused on areas with strong land–climate feedbacks, including the Amazon (Shukla *et al.* 1990; Costa and Foley 2000), the Sahel (Wang and Eltahir 2000), and boreal regions (Bonan *et al.* 1992).

Although coupled GCMs mathematically represent many of the physical mechanisms that are lacking in simpler models, they have key practical and scientific limitations. First, despite most of the models being in the public domain, practical access is extremely limited because of their complexity and computer hardware requirements. Few people are able to quickly learn how to use such systems. Second, many GCMs still suffer from scientific and technical problems, including somewhat unrealistic simulations of climate (at least at the local and regional level, especially in terms of critical processes like precipitation), and the lack of sufficient geographic detail. In addition (although not an inherent limitation of GCMs), applications of GCMs have focused on changes in GHG emissions. For example, despite the known land–atmosphere feedbacks, land-use change was not a primary forcing function of the models used in the Intergovernmental Panel on Climate Change (IPCC) scenarios. Feddema *et al.* (2005) demonstrate that including land-use change in the IPCC scenarios results in substantially different regional climate projections.

As an alternative to using coupled GCMs, we have developed a method that uses observed (not simulated) climate data and a simple land-surface model to estimate the potential influence of ecosystems on climate through biophysical climate regulation. The land-surface model is used to estimate the surface energy and water balances, and how it is affected by changes in land cover. Thereafter, we estimate the resulting changes in air temperature and humidity in the lower atmosphere, based on observed climate data and several simple assumptions of atmospheric physics (Figure 3).

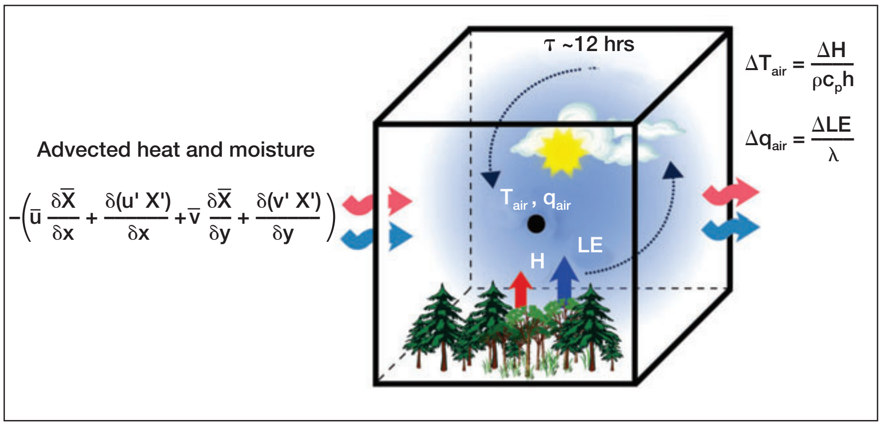

Figure 3. *Estimating biophysical regulation of climate by ecosystems. Near-surface atmospheric heat and moisture are strongly influenced by sensible (H) and latent (LE) heat fluxes from the land. These fluxes generally mix within a few hundred meters (~ 250–500 m) of the surface for several hours (turnover time [τ] ~ 12 hours) before leaving the mixing layer. The temperature and moisture response to land-cover change can be estimated as a function of changes in the energy fluxes (H and LE), the air density (ρ), specific heat capacity of the air (c_p), the height of the mixing layer (h), and the latent heat of vaporization (λ). The influence of wind-transported, or advected, heat and moisture can be calculated by means of observed climate data, where $\bar{X}$ is the monthly average advected heat (H) or moisture (q),* u *and* v *are the horizontal wind directions, and X' adjusts the monthly averages by accounting for sub-daily turbulence.*

In our land-surface model, we first simulated energy fluxes from ecosystems in a natural, undisturbed setting (ie "potential" vegetation). We estimated the total energy that ecosystems absorb, or net radiation, using the 1961–1990 average climatology (New *et al.* 2002), and previously defined approaches for quantifying solar input (Prentice *et al.* 1993; Friend 1998) and long-wave radiation (Linacre 1968). Short-wave energy reflected from the surface is determined as a function of the surface albedo, through values derived from the literature (Oke 1987; Baldocchi *et al.* 2000; Eugster *et al.* 2000) and previous modeling efforts. Deforestation and other land clearings generally increase the albedo, thus reducing the solar radiation absorbed by the surface. Although soil moisture affects the albedo of bare soil (moisture decreases albedo), soil albedo is not dynamic in our approach, because we only present annual differences in temperature and moisture.

The net radiation (R_{net}) determines the total energy available for latent energy (LE) and sensible heat (H) fluxes to the atmosphere. We calculated LE following the Penman (1948) and Priestley and Taylor (1972) formulations of energy-balance/water-balance coupling, using a modified approach developed by Ramankutty *et al.* (2002) and Gerten *et al.* (2004). Sensible heat was calculated by mass balance (H = R_{net} – LE), assuming that net heat storage in vegetation and soils was negligible at the timescales studied.

To estimate the potential effects of land-cover change on climate regulation, we compared the "potential vegetation" scenario with a "bare ground" scenario. While neither of these is realistic today, they enabled us to place boundaries on the potential range of climate regulation by ecosystems.

For ease of interpretation, we converted the difference in latent heat between the two scenarios from W m^{-2} to mm H_2O (using the latent heat of vaporization constant as a function of temperature) to express the effects of land-use change as units of precipitable water, or the surface-layer moisture content. We then estimated the temperature response of the lower atmosphere to the sensible heat flux by assuming standard heat capacity and air density values for 0°C (Wallace and Hobbs 2006), and 12 hours of heating (to correspond to a typical diurnal cycle of heating during the day and cooling at night) within an average mixing layer that varies from ~ 500 m at the equator to ~ 250 m at the poles. This simplified mixing layer is similar to the annual average planetary boundary layer height estimated from observations (Uppala *et al.* 2005) and from a control run of the Community Atmosphere Model Version 3 (CAM3; Collins *et al.* 2006; Hurrell *et al.* 2006).

We used this simple approach to examine the biophysical regulation of climate by ecosystems, by estimating changes in the surface latent and sensible heat fluxes from two simulations: one with complete vegetation cover (potential vegetation), and another where the vegetation has been removed (bare ground). By comparing the two simulations, we estimated the influence of ecosystems on temperature and moisture content in the lower atmosphere.

Through this approach, our results show that the biophysical regulation of climate by ecosystems has the greatest influence on air temperature and moisture in boreal and tropical regions. In boreal regions, vegetation removal causes a ~ 1.5°C temperature decrease and ~ 0.3 mm d^{-1} decrease in liquid water content in the lower atmosphere, whereas tropical areas exhibit a 1.5°C temperature increase and a 1.0 mm d^{-1} decrease in liquid water content in the lower atmosphere (Figure 4a, b). These changes of ± 1.5°C could magnify or offset the 2.0–5.4°C warming from GHGs projected for 2100 in a high impact scenario (A2) of the IPCC's Fourth Assessment Report (IPCC 2007). In other forest, grassland, and shrubland biomes, annual average temperature differences in response to vegetation removal

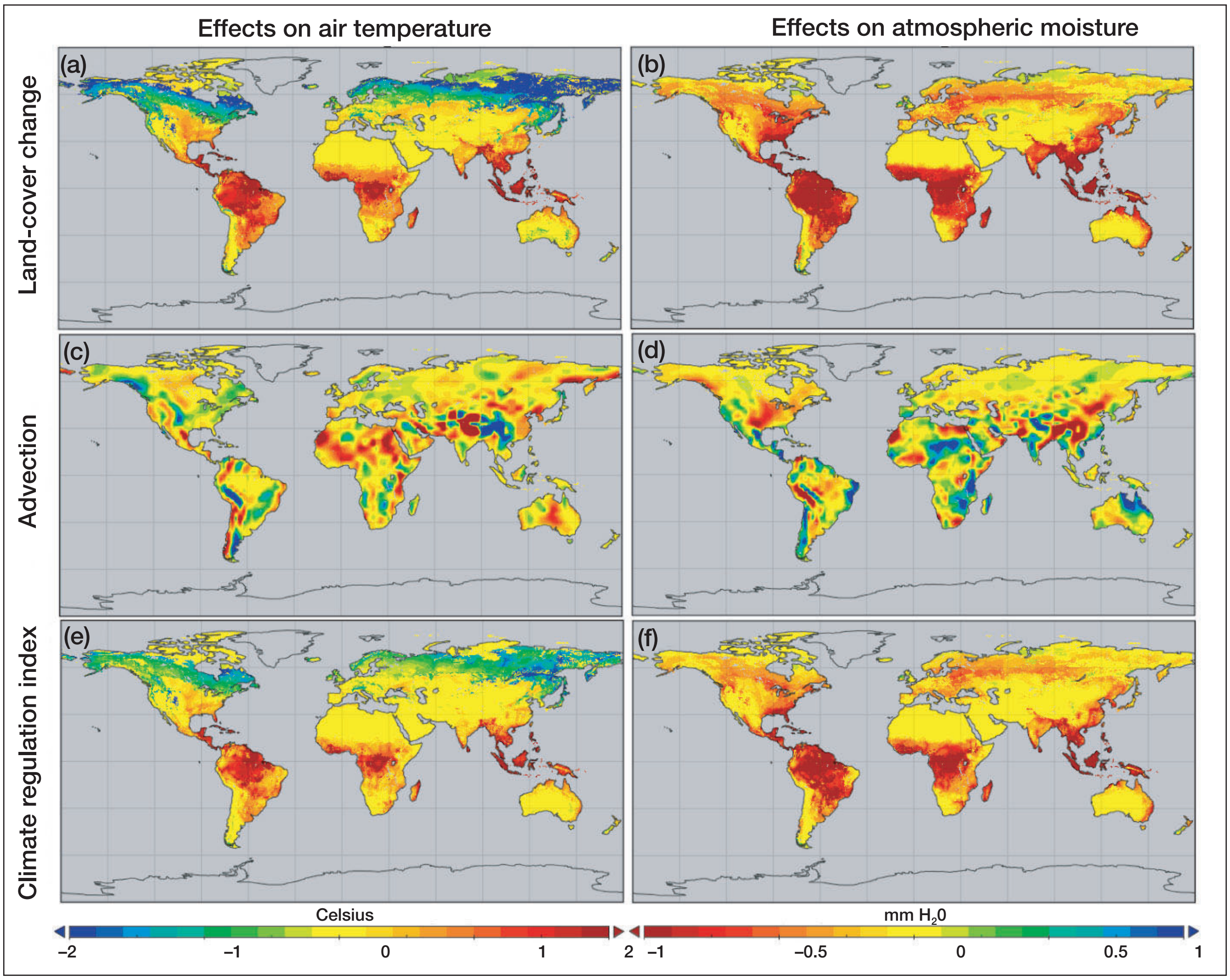

Figure 4. *Changes in air temperature and moisture from land-cover change and atmospheric circulation. Here, we have first estimated the effects of vegetation removal on the near-surface air temperature and humidity (expressed as changes in air temperature, °C, and moisture, in mm of water) across the globe (a and b). Large-scale transport of heat and moisture by wind is also estimated (c and d). A comparison of the two (a and b versus c and d) shows the relative impacts of local, biophysical processes and large-scale atmospheric transport on climate. In the bottom two panels (e and f), we combined both factors to create a climate regulation index, which estimates the effects of land-cover change on climate, but modulated by the effects of wind-transported heat and moisture.*

ranged from –0.3°C (temperate evergreen forests) to +0.5°C (savannas and dense shrublands). In these biomes, the annual average change is lower because seasonal cooling and warming offset one another. Other, GCM-based, coupled modeling experiments that replaced natural vegetation with bare soil conditions also estimated that the climatic response of land-cover change was strongest in the tropics and boreal regions (Snyder *et al.* 2004).

As seen in our analysis, removing boreal forests has a net cooling effect on the climate, in agreement with several other studies (Bonan *et al.* 1992; Betts 2000; Snyder *et al.* 2004; Figure 4a, b). This cooling effect primarily results from reduced absorption of solar radiation due to the higher reflectivity of snow cover relative to dark trees. Less sensible heat is released from the ecosystem, resulting in less loading of heat to the local atmosphere.

Although the directional response (cooling) and pattern are consistent, our estimates of ~ 1.5°C cooling are somewhat modest as compared with those from coupled GCM model simulations (Bonan *et al.* 1992; Snyder *et al.* 2004). These differences are most likely because we do not model the effects of land-cover change on atmospheric aerosols, cloud formation, or sea-ice feedbacks that are included in more complex models. For example, lowered temperatures increase sea ice, which in turn increases regional albedo, further reducing air temperatures. Removing the entire boreal forest could result in longer winter seasons as a result of increased sea ice (Bonan *et al.* 1992) and a reduced planetary boundary layer thickness (Snyder *et al.* 2004). Our approach does not account for either of these feedbacks.

In contrast to the boreal region, removing tropical forests warms the land surface. Despite the decrease in absorbed radiation, air temperatures can still increase because a greater portion of the absorbed radiation is released as sensible heat (Figure 2). These results are in line with those from previous studies of deforestation that used coupled models for the tropics as a whole (Zhang *et al.* 1996; Snyder *et al.* 2004) and for the Amazon Basin (Shukla *et al.* 1990). For example, the previously mentioned studies estimate 1.5–3.3°C warming that corresponds to increases in sensible heat (~ 10–30 W m^{-2}) and decreases in latent heat (~ 30–80 W m^{-2}) in response to deforestation (Shukla *et al.* 1990; Zhang *et al.* 1996; Snyder *et al.* 2004). Our analysis estimates a ~ 1.5°C warming and a decrease of ~ 30 W m^{-2} in latent heat as a result of tropical deforestation. This also represents a ~ 1.1 mm d^{-1} reduction in lower atmosphere moisture.

Other pan-tropical climate studies estimate smaller effects of land use on air temperature and moisture in tropical forests in Africa and southeastern Asia (Zhang *et al.* 1996; Snyder *et al.* 2004). In these regions, atmospheric transport of heat and water vapor from the oceans to land reduces the influence of land-cover change effects. Figure 4, a and b, shows that when atmospheric circulation is not considered, the climatic changes in other tropical areas are similar to changes estimated for the Amazon Basin.

Large-scale influences in regional climate

The analysis in the previous section neglects the horizontal transport of heat and moisture. In areas with strong, large-scale circulation, the effects of local land-cover changes on local climate are modulated by the influence of wind-transported heat and moisture. This is termed *advection* in meteorology. Although land-cover change alters the surface roughness and potentially the temperature and moisture gradients, large-scale advection patterns are largely driven by global and regional atmospheric circulation patterns, but are often modified by meso-scale atmospheric systems, such as monsoons and lake breezes.

To account for the influence of wind on climate – compared to the effects of ecosystems and land-cover change – we calculated the global patterns of advected heat and moisture using the National Centers for Environmental Prediction (NCEP) re-analysis data (Kalnay *et al.* 1996). These data represent the three-dimensional structure of the atmosphere, including estimates of temperature, humidity, and wind, among many other variables, for every 6-hour period, at a spatial resolution of 2.5 degrees. We used the 1961–1990 re-analysis data for wind, temperature, and specific humidity to calculate the monthly average horizontal advection between grid cells for each of the 17 pressure levels, adjusting for hourly turbulence. We averaged data for the entire month, using assumptions that were consistent with the air density, heat capacity, and boundary layer assumptions previously mentioned in this section and the preceding section. This analysis resulted in estimates of large-scale transport of heat and moisture. We acknowledge that other studies show that circulation (and advection) changes in response to land-cover change itself, and can be complex in heterogeneous landscapes (Baidya and Avissar 2002), but here we assume that large-scale transport patterns remain fixed and outweigh the influence of local land-cover change on advection.

Figure 4, c and d, illustrates global patterns of advected heat and moisture (expressed as °C and mm H_2O, respectively) averaged within the lower mixing layer of the atmosphere. In Figure 4c, positive values (red) denote warm-air advection. That is, warmer air is advected into the region by wind, making local conditions warmer, and is shown in red. Conversely, the blue areas in Figure 4c indicate that cooler air is transported into the region. In Figure 4d, positive (blue) values indicate that moisture is transported into the region and the red regions imply that moisture is being advected out of the region.

These figures illustrate some key points. First, solar heating is a major driver of atmospheric circulation. As a result, transport of heat is generally strongest near the equator and weakest at the poles. However, ocean circulation patterns can also have a strong influence, which offsets that of solar radiation. Second, the high advection of heat and moisture are correlated in some areas, such as eastern South America and eastern Africa, due to advection of heat and moisture from the oceans to land. However, other areas, such as the Amazon, Congo, North American Great Plains, and Mongolian steppe experience weak annual advected heat, but strong advected moisture (gains or losses).

Developing a climate regulation index

Estimating changes to heat and water fluxes in response to land-cover change may overstate the actual response if advection is not considered. The influence of land-cover change on air temperature and moisture (Figure 4a, b) may be small relative to the influence of advection (Figure 4c, d). To quantify climate regulation by ecosystems, we propose an index that scales the influence of land-cover change (Figure 4a, b) by the relative influence of advection. By combining the two dominant processes that influence regional variations in climate (biophysical regulation from local land surface processes, and advection of heat and moisture from large-scale atmospheric circulation) we can identify places where land-cover change has a strong influence on regional climate.

Equations 1 and 2 describe a climate regulation index that includes the direction and magnitude of change, as well as the influence of advection:

Eq 1:

$$\text{Heat regulation index} = \Delta H * \frac{|\Delta H|}{|\Delta H| + |H_{adv}|}$$

Eq 2:

$$\text{Moisture regulation index} = \Delta q * \frac{|\Delta q|}{|\Delta q| + |q_{adv}|},$$

where ΔH and Δq are changes in sensible and latent heat fluxes, respectively, in response to land-cover change, and H_{adv} and q_{adv} are wind-transported heat and moisture, respectively.

The first term of each index (ie ΔH and Δq) is the effect of land-cover change on temperature and moisture of the surface-layer climate (Figure 4a, b). Large-scale influences on regional climate, calculated using methods described in the previous section and Figure 3, are illustrated in Figure 4, c and d. The second term of the index combines the effects of land-cover change and large-scale influences and is the relative contribution of land-cover change on advection. Thus, the influence of transport of heat and moisture by upwind sources is accounted for (the heat and moisture effects of land-cover change are not transported downwind). By multiplying the two terms, the effects of land-cover change are scaled relative to the influence of advection to create the climate regulation index (Figure 4e, f). As the strength of the advection increases, the index approaches zero.

Figure 4e and f shows the climate regulation indices, as defined above. The potential of ecosystems to regulate climate (Figures 4a, b) is reduced in areas where large influxes of heat and moisture are transported from the oceans to land. The effects of this scaling index are most pronounced in areas with monsoonal climates, such as eastern Brazil, the east coast of central Africa, and western India. The results for these three regions are consistent with those from coupled modeling experiments for the pan-tropics (Zhang *et al.* 1996; Snyder *et al.* 2004), where the effects of land-cover change on air temperature are lower in areas of high amounts of advected heat. In contrast, the scaling effect of the climate regulation index had limited influence in some areas defined as "hotspots" of land–atmosphere coupling (Koster *et al.* 2006), including the Sahel, Congo, western Amazonia, and the western Great Plains. In general, the climate regulation index values were weaker than the effects of land-cover change in the boreal region, indicating the strong influence of advected heat and moisture.

Limitations of the climate regulation index

Although the approach proposed here approximates results generated by more complex modeling approaches, it is not intended to address all questions related to climate regulation by ecosystems. Key limitations relate to land management and atmospheric physics.

Changes in air temperature and moisture will vary with different land-cover types and management practices. Our approach compared a natural vegetation scenario to a bare-ground scenario and thus estimated the potential contribution of natural ecosystems to biophysical climate regulation, but conversion of natural land to other land-cover types can have different results. For example, replacing forest with bare ground in this study generally increased air temperature, however, in the US, conversion of forests to croplands generally decreases air temperature (Bonan 1999, 2001). Both bare ground and croplands absorb less incoming sunlight, but croplands and forests transpire similar amounts of water. As a result, croplands release less energy as sensible heat and the air temperature is cooler. Cropland irrigation also decreases air temperature in the northern mid-latitudes (Sacks *et al.* 2008).

The atmosphere responds dynamically to land-cover changes. Here, we prescribed a mixing layer height of the near-surface atmosphere that approximates that in previous studies (~ 500 m at the equator and ~ 250 m at the poles; Uppala *et al.* 2005; Collins *et al.* 2006; Hurrell *et al.* 2006). However, this mixing layer height will vary seasonally and in response to land-cover change (Oke 1987). A dynamic mixing layer height would likely improve seasonal estimates of changes to air temperature and moisture in response to land-cover change. In addition to the effects of land-cover change on the mixing layer height, the simplified atmospheric physics assumed here ignore the important feedback between land and the atmosphere. This feedback has been shown to be particularly important in tropical and boreal forest regions, as well as in additional hotpots – the Sahel region of Africa, North American Great Plains, and India – identified through the Global Land–Atmosphere Coupling Experiment (Koster *et al.* 2006). Finally, the proposed index does not account for heat or moisture transported downwind, which particularly occurs in areas of strong circulation.

Conclusions and potential applications

This proposed approach represents a first step toward developing a simple index of climate regulation by ecosystems. However, it is not intended to replace more complex modeling of the climate system. Rather, this physically based metric indicates the potential influence of land-cover change without requiring a highly complex model. However, "offline" models that estimate the effects of land-cover change on climate without considering atmospheric circulation effects give inaccurate results for areas dominated by advection, such as monsoonal climates. By combining the effects of land-cover change with observed estimates of advection of heat and moisture, the index we describe here provides results that are roughly comparable to those using coupled GCMs.

If this simplified approach were incorporated into accessible software tools, ecological researchers and resource managers could make first-order estimates of the effects of land-cover change on air temperature and moisture within minutes, instead of using thousands of computer processor hours. This would enable more rapid assessment of policy and management questions related to the effects of potential land-cover change on biodiversity conservation, agricultural production, and human health. For example, resource managers could quickly generate estimates of changes in air temperature and moisture under alternative land-cover scenarios. Such results would provide insights into the location or extent of restoration or preservation needed to maintain the "climatic envelope" for conserving biodiversity, producing crops, or maintaining other critical ecosystem services.

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