

Climate-regulation services of natural and agricultural ecoregions of the Americas

Kristina J. Anderson-Teixeira^{1,2,3}, Peter K. Snyder⁴, Tracy E. Twine⁴, Santiago V. Cuadra⁵, Marcos H. Costa^{6,7} and Evan H. DeLucia^{1,2,3}★

Terrestrial ecosystems regulate climate through both biogeochemical (greenhouse-gas regulation) and biophysical (regulation of water and energy) mechanisms^{1,2}. However, policies aimed at climate protection through land management, including REDD+ (where REDD is Reducing Emissions from Deforestation and Forest Degradation)³ and bioenergy sustainability standards⁴, account only for biogeochemical mechanisms. By ignoring biophysical processes, which sometimes offset biogeochemical effects^{5,6}, policies risk promoting suboptimal solutions^{1,2,4,7–10}. Here, we quantify how biogeochemical¹¹ and biophysical processes combine to shape the climate regulation values of 18 natural and agricultural ecoregions across the Americas. Natural ecosystems generally had higher climate regulation values than agroecosystems, largely driven by differences in biogeochemical services. Biophysical contributions ranged from minimal to dominant. They were highly variable in space, and their relative importance varied with the spatio-temporal scale of analysis. Our findings reinforce the importance of protecting tropical forests^{7,10,12,13}, show that northern forests have a relatively small net effect on climate^{5,10,13}, and indicate that climatic effects of bioenergy production may be more positive when biophysical processes are considered^{14,15}. Ensuring effective climate protection through land management requires consideration of combined biogeochemical and biophysical processes^{7,8}. Our climate regulation value index serves as one potential approach to quantify the full climate services of terrestrial ecosystems.

Anthropogenic land use has been, and will continue to be, a major driver of the climate system^{6,16–18}. In terms of biogeochemical drivers, land-use change and agriculture together account for over 25% of global greenhouse-gas (GHG) emissions¹⁹. From 1990 to 2007, gross CO₂ emissions from tropical deforestation were equal to ~40% of global fossil fuel emissions¹⁸. In recent years, agriculture has contributed ~14% of total global GHG emissions^{19,20}.

Terrestrial ecosystems also strongly affect climate through their control over albedo and evapotranspiration^{3,6,8,16,21,22}. Vegetated surfaces—especially forests—typically have lower albedos than bare ground and therefore absorb more incoming solar radiation. The reduction in net radiation (R_n) associated with deforestation has a cooling effect on the climate^{5,22,23}—sometimes even outweighing GHG-induced warming^{5,18}. Counteracting this, clearing vegetation reduces evapotranspiration and associated latent heat flux (LE). Without the vegetation, energy normally used to evaporate water instead heats the land

surface^{6,8,14,22,23}. Understanding the counteracting effects of R_n and LE is key to quantifying the climate regulation values (CRVs) of different ecosystems¹.

Policies that affect land use may serve as one effective strategy contributing to climate change mitigation^{2,12} or may inadvertently exacerbate the problem²⁴. Major national and international initiatives for reduction of GHG emissions, including bioenergy mandates and the REDD+ initiative for reduction of deforestation³, enact mechanisms that will substantially alter land-use patterns. However, current paradigms for valuation of ecosystem climate services are limited in that most account only for biogeochemical climate services. By ignoring biophysical forcings from land-use change^{5,6}, policy initiatives run the risk of failing to advance the best climate solutions^{1,2,4,7–10}.

Quantifying ecosystem climate services remains an ongoing challenge. The GHG value of maintaining an ecosystem (or, conversely, the cost of clearing it) depends on existing carbon stocks, ongoing ecosystem–atmosphere GHG exchange, likelihood of natural disturbance and the time frame of analysis—factors that are all incorporated in the recently developed GHG value (GHGV) metric¹¹. In terms of biophysical services, the climate impacts of changes in albedo can be directly compared with those of GHGs by computing the effect of a local change in R_n on global mean radiative forcing⁵. Incorporating changes in LE presents a greater challenge. More evaporation can promote cloud cover, affecting planetary albedo and the global radiation balance. The direct cooling effects of LE are locally significant^{8,14,22,23}, but ultimately cancel at the global scale, because the water eventually condenses⁸. A further challenge to combining biogeochemical and biophysical services lies in their disparate timescales: whereas biophysical processes change with vegetation cover, biogeochemical forcings have a legacy because GHGs remain in the atmosphere—and thereby impact the climate—for many years following their release.

Here, we combine biogeochemical (GHGV; ref. 11) and biophysical climate regulation services into an integrated index of ecosystem CRV, which expresses changes in the surface energy balance relative to a bare-ground baseline in CO₂ equivalents—a common currency for carbon accounting. This index combines locally weak but globally distributed GHG forcings with strong local biophysical forcings by dividing local effects by global surface area. Because the non-local biophysical effects of changes in atmospheric transport of water are not included in this calculation, CRV does not characterize net effects on global climate, but rather provides an integrated index of the direct effects of land clearing on the land surface energy budget.

¹Energy Biosciences Institute, University of Illinois, Urbana, Illinois 61801, USA, ²Plant Biology, University of Illinois, Urbana, Illinois 61801, USA, ³Global Change Solutions, LLC, Urbana, Illinois 61801, USA, ⁴Soil, Water and Climate, University of Minnesota, St Paul, Minnesota 55108, USA, ⁵Department of Atmospheric Sciences, Federal Center of Technological Education Celso Suckow da Fonseca (CEFET/RJ), Rio de Janeiro, RJ 20271-110, Brazil, ⁶Federal University of Viçosa, Viçosa, MG 36570-000, Brazil, ⁷Ministry of Science, Technology and Innovation, Brasília, DF 70067-900, Brazil.

★e-mail: delucia@life.illinois.edu.

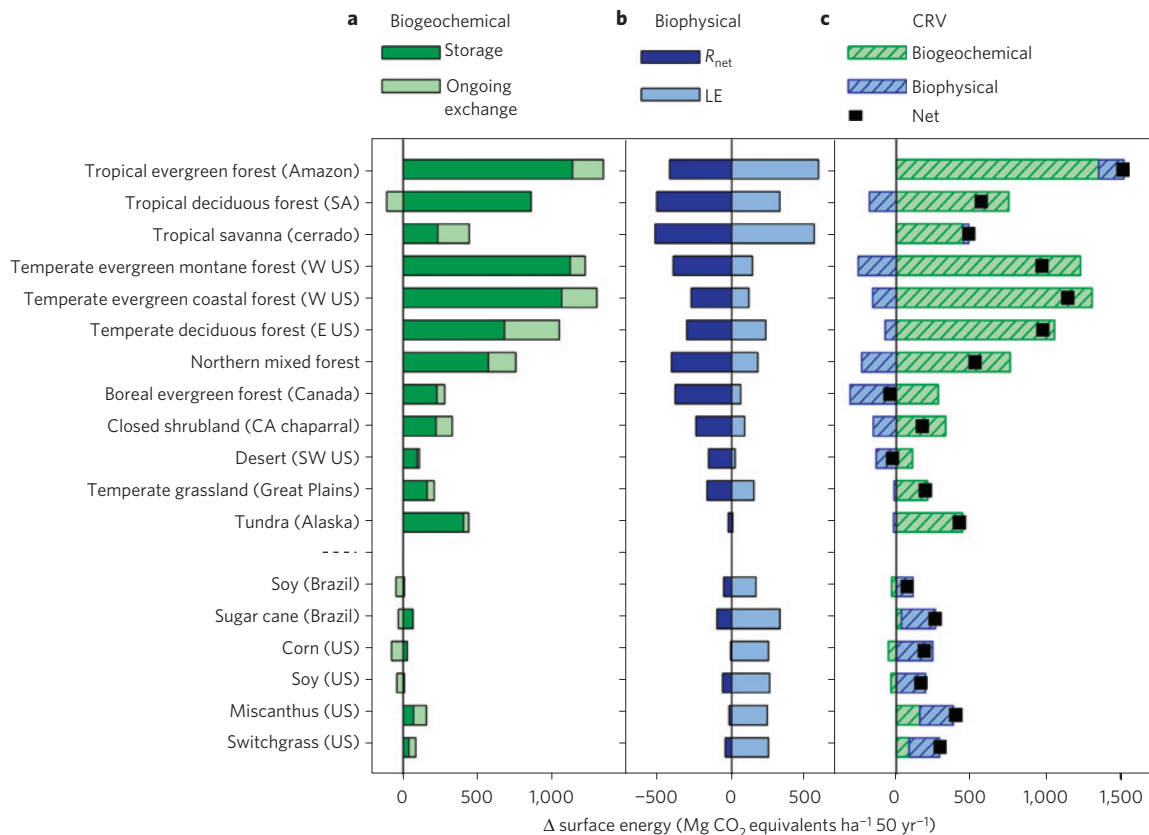


Figure 1 | Biogeochemical and biophysical climate services (relative to a bare-ground baseline) of natural and agricultural ecoregions of the Americas. **a, b,** Contributions from GHGs (**a**), including both the GHGs that would be released on land clearing and ongoing GHG exchange, and ΔR_n and ΔLE (**b**), extrapolated to the global scale by dividing local effect by global surface area (indirect effects excluded). **c,** These are combined to yield an integrated measure of CRV. Values are calculated over a 50-year time frame ($T_E = T_A = 50$ years).

CRV involves two time frames: the ecosystem time frame (T_E) over which ecosystem–climate interactions are characterized, and the analytical time frame (T_A) over which radiative forcing is integrated and converted into CO_2 equivalents ($T_A \geq T_E$).

We quantified both biogeochemical and biophysical ecosystem climate services of 18 ecoregions across the Americas (12 natural and six agricultural; Supplementary Table S1). Specifically, we quantified GHGV using the model of ref. 11 in combination with a compilation of empirical data (see Methods and Supplementary Information for details). We quantified the impacts of clearing vegetation on R_n and LE using the land surface models IBIS and AgroIBIS (refs 25–29). CRV was calculated according to equation (1) (Methods) using a time frame of 50 years ($T_E = T_A = 50$ years). Choice of T_E and T_A is consequential; therefore, we also examined effects of varying time frames.

Both biogeochemical and biophysical factors contributed meaningfully to the CRV of terrestrial ecosystems (Fig. 1). For most ecoregions, the largest contribution came from GHGV. In general, natural ecosystems had much higher GHGVs than agroecosystems (Fig. 1a; Supplementary Fig. S2; ref. 11). For natural ecosystems, most of this value came from carbon stocks that would be released to the atmosphere as CO_2 on land clearing, whereas some came from ongoing uptake of CO_2 . In contrast, intensively managed agroecosystems had minimal carbon stocks but large contributions from N_2O emissions (Supplementary Fig. S2). Perennial grass biofuel crops had slightly higher carbon storage and lower N_2O emissions than traditional row crops, giving them higher GHGVs.

Biophysical processes strongly affected the CRV of some ecosystems (Fig. 1). In all ecoregions, clearing of the vegetation decreased R_n , resulting in a cooling effect that was greatest in

forests and savanna ($\Delta R_n > 20 \text{ W m}^{-2}$) and least in agroecosystems and tundra ($\Delta R_n < 10 \text{ W m}^{-2}$; Figs 1b, 2; Supplementary Fig. S3). In contrast, clearing of vegetation reduced LE , resulting in a warming effect that was greatest in tropical forests and savanna ($\Delta LE \approx 30 \text{ W m}^{-2}$ in the Amazon and the cerrado ecoregions) and lowest in cold or dry regions where evapotranspiration is lower (Figs 1b, 2 and Supplementary Fig. S3). The clearing of agroecosystems resulted in a rather larger reduction of LE ($\Delta LE > 10 \text{ W m}^{-2}$). In most natural ecosystems, except Amazon forest and cerrado, ΔR_n typically outweighed ΔLE such that cooling was the net biophysical effect of land clearing, whereas net biophysical services were positive in agroecosystems (Fig. 1b). Even if increased net radiation (warming) is completely compensated by increased evapotranspiration (cooling), the ecosystem still might act to cool the climate indirectly, for example if increased evapotranspiration enhances cloud cover, and thus planetary albedo. Tropical forests in particular cool the climate through such indirect mechanisms⁶; results from a coupled atmosphere–biosphere modelling study using the same vegetation model (IBIS; ref. 22) suggest that their climate benefit is underestimated here by $\sim 6 \text{ W m}^{-2}$. Biophysical forcings were highly variable in space (Fig. 2 and Supplementary Fig. S3), implying that average values presented here (Fig. 1) are not representative of all locations within a given ecoregion.

In natural ecosystems, biogeochemical climate services generally exceeded biophysical services (Fig. 1c), with the notable exceptions of Canadian boreal evergreen forest and US Southwest desert. In contrast, biophysical forcings dominated in agroecosystems. In the tropics, consideration of biophysical processes increased the value of forests relative to agroecosystems, whereas this difference was reduced in temperate regions.

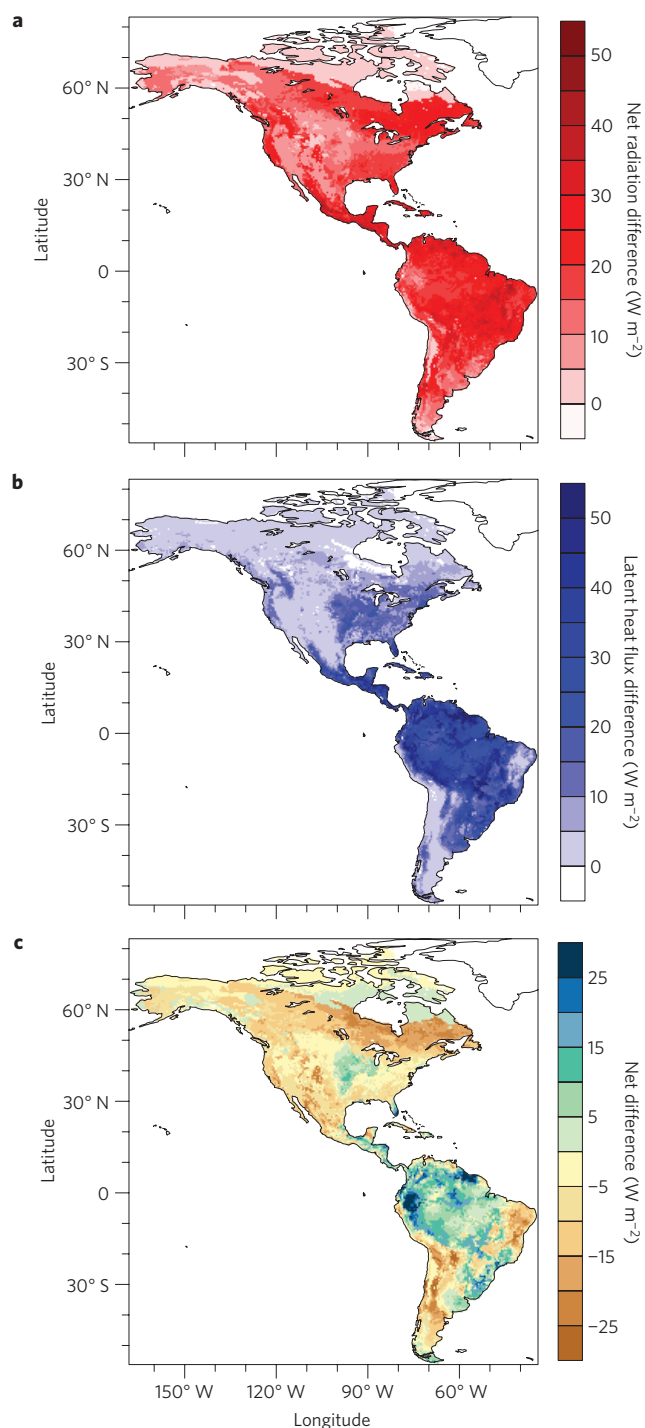


Figure 2 | Spatial variation in biophysical climate services of ecosystems (relative to a bare-ground baseline). **a–c**, ΔR_n (**a**), ΔLE (**b**) and net biophysical forcings ($-\Delta R_n + \Delta LE$) (**c**) of natural vegetation relative to a bare-ground baseline.

Both CRV and its relative contributions from biogeochemical and biophysical processes are highly dependent on the spatial and temporal scales under consideration. At the local scale, biophysical forcings dwarfed GHG forcings; for example, clearing one hectare of tropical evergreen forest would produce a local GHG-derived forcing of $1.4 \times 10^{-9} \text{ W m}^{-2} \text{ yr}^{-1}$ (averaged over the first 50 years since clearing) and a net biophysical forcing of $8.6 \text{ W m}^{-2} \text{ yr}^{-1}$. Divided by Earth's land surface area for comparison with global GHG forcings, however, biophysical

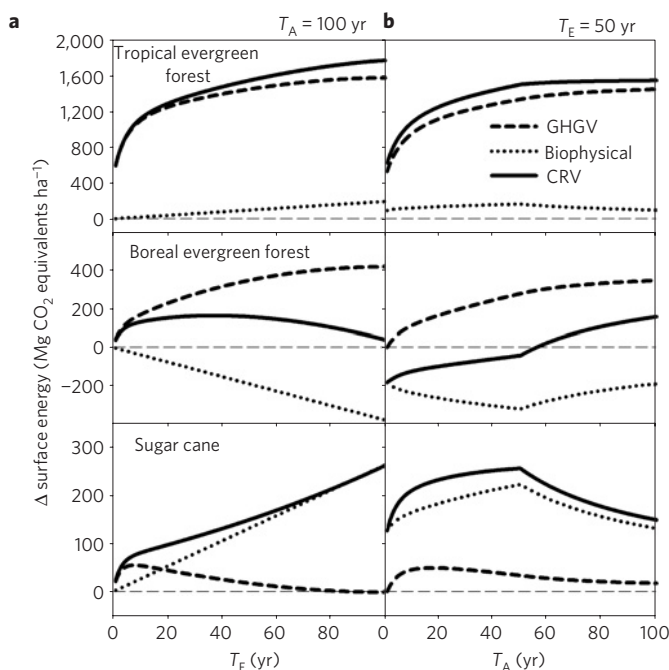


Figure 3 | Dependence of climate-regulation services on the temporal scale of analysis. **a, b**, Responses of CRV and its biogeochemical (GHGV) and biophysical components of three different ecoregions to years over which ecosystem-atmosphere exchanges are characterized, (T_E) (**a**), and years over which radiative forcing is integrated and converted into CO_2 equivalents (T_A) (**b**). For each analysis, the other time dimension is held constant ($T_A = 100$ years in **a**; $T_E = 50$ years in **b**). Interactive effects of T_E and T_A on the CRVs of these ecosystems are illustrated in Supplementary Fig. S4.

forcings were often outweighed by GHG effects (Fig. 1c). Thus, whereas biogeochemical services are often more important for the protection of global climate (Fig. 1c), protection of local climate—which may often be more relevant for the actual impacts of climate change on humans and terrestrial ecosystems—must consider biophysical processes^{8,9}.

CRV was also dependent on temporal scale, varying with both T_E and T_A , and this temporal dependence differed among ecoregions (Fig. 3, Supplementary Fig. S4). In the boreal evergreen forest and US Southwest desert, the sign of CRV depended on the time frame selected (Supplementary Fig. S4). The relative importances of biogeochemical and biophysical services varied with T_E and T_A (Fig. 3). Because biophysical forcings accumulated linearly over T_E , whereas the rate of change in GHGV typically decreased as T_E increased¹¹, the relative importance of biophysical forcings generally increased with T_E (Fig. 3a). In contrast, the relative importance of biophysical forcings was reduced when T_A exceeded T_E (Fig. 3b). This occurs because biophysical forcings cease at the end of T_E , whereas biogeochemical forcings continue to accrue because GHGs remain in the atmosphere. Thus, GHGV tends to stabilize at high $[T_A - T_E]$ (ref. 11), whereas biophysical contributions decrease with $[T_A - T_E]$. Together, these effects yield a complex and variable time dependence of CRV (Fig. 3, Supplementary Fig. S4). Treatment of time is therefore consequential and requires careful consideration^{4,11}. Because land-use changes are typically long lasting and because GHGV changes rapidly over the first 20 years (Fig. 3; ref. 11), T_E should be no less than 20 years. On the other hand, uncertainty regarding the future state of ecosystems grows with T_E , such that uncertainty will be relatively high at $T_E > 50$ years, and T_E should not exceed 100 years. To avoid under-representation of biophysical effects, T_A should equal T_E .

Consideration of biophysical in addition to biogeochemical ecosystem climate services has important implications for land management decisions in an era of climate change. Whereas consideration of biophysical processes generally does not change the basic paradigm that forests provide the highest climate regulation services followed by other natural ecosystems and then agroecosystems¹¹, it does shift the relative values of some ecoregions. For example, inclusion of biophysical forcings increases the CRV of tropical forests while dramatically decreasing, and sometimes even reversing⁵, the value of northern forests (Figs 1, 3, Supplementary Fig. S4; ref. 1). Indeed, other studies have shown that tropical deforestation increases mean global surface temperature, whereas deforestation in temperate and boreal regions has, if anything, a net cooling effect^{1,22}. This highlights the critical importance of tropical forests for climate protection^{1,2,6,21}, supporting the argument that efforts to mitigate climate change through avoided deforestation or afforestation efforts (for example, REDD+; ref. 3) will be most effective if focused on tropical forests^{2,10,13}.

Our results also support recent findings that the net climate impact of bioenergy production may be more positive than previously estimated^{14,15} if tropical deforestation is avoided. From a biophysical standpoint, croplands (including bioenergy crops) in temperate regions tend to have climate benefits over natural ecosystems (Fig. 1b)—a result that is consistent with other studies^{16,22}. Although this effect does not rival the warming effect of GHGs on global scales, it somewhat reduces the climate costs of this type of land-use change^{14,15}. In addition, dedicated perennial grass bioenergy crops tend to have higher CRVs than their traditional row-crop counterparts (Fig. 1c). Thus, the climate mitigation potential of bioenergy production—particularly from perennial grasses—may be improved relative to previous estimates if perennial grass bioenergy crops replace current agroecosystems and tropical deforestation is avoided.

Our CRV metric condenses a complex reality into a simple number and, in doing so, masks some important underlying considerations. First, because biogeochemical and biophysical dynamics operate over vastly different spatio-temporal scales, it is possible to foresee a variety of different ways in which they could be combined into a climate regulation metric. For example, an alternative approach would be to represent biophysical effects in terms of their effects at the top of the atmosphere—an approach that would accurately characterize ecosystems' effects on Earth's radiative balance but obscure the very real significance of strong localized biophysical effects^{8,9,22}, which have greater significance for both humans and ecosystems. Second, although units of CO₂ equivalents are practical in that this is a broad currency and provides a reasonable framework for representation of time, these units must not be taken to imply equivalency of actions with disparate effects in other dimensions. For example, even if boreal deforestation would provide an overall cooling effect through biophysical mechanisms (Fig. 1, but see Fig. 3, Supplementary Fig. S4; ref. 5), it would exacerbate the root problem of increasing atmospheric CO₂ concentrations and associated problems such as ocean acidification.

Our findings demonstrate the importance of considering biophysical, in addition to biogeochemical, climate regulation services of ecosystems. Although the complexity of quantifying ecosystem climate services presents a challenge for policy^{4,7,9,30}, ignoring biophysical processes may lead to suboptimal land-use policies^{1,2,4,7–10}. By combining GHGV (ref. 11) with biophysical effects, CRV may help to inform policy decisions concerned with ecosystem climate services. In the face of increasing land-use pressures driven by a growing world population and an emerging bioenergy industry, together with the increasingly urgent need to protect the climate system, such quantification of ecosystem climate regulation services will be essential to constructing wise land-use policies.

Methods

We quantified climate regulation services for 12 natural and six agricultural ecoregions in the Western Hemisphere (Supplementary Table S1; Fig. S1). Climate regulation services were defined relative to a baseline of bare soil and depleted organic-matter stocks¹¹. The full effect of land-use change is therefore the difference between values for two different ecosystem types.

The data required to calculate CRV could be derived in a variety of ways; here, we used empirically measured estimates of biogeochemical parameters and modelled biophysical processes using IBIS (refs 25,29) for natural ecosystems and AgroIBIS (refs 26–29) for agroecosystems. For each ecoregion, parameters for the calculation of GHGV (for example, carbon stocks, net ecosystem exchange, N₂O and CH₄ emissions) were compiled from the literature and averaged across each ecoregion (Supplementary Tables S2–S4). When there were not sufficient data available for an ecoregion, we used global averages for that biome type¹¹. Biophysical forcings from clearing an ecosystem were simulated in IBIS/AgroIBIS by carrying out a simulation with vegetation present and one with bare ground. Differences in surface R_n and LE between the two simulations (ΔR_n and ΔLE , respectively) were calculated and averaged over the ten-year period (1991–2000) meant to reflect an 'average' climate period. These values were then averaged across spatially delineated ecoregions (Supplementary Table S1, Fig. S1), yielding means and spatial standard deviations for each region (Supplementary Fig. S3).

GHGV was calculated as in ref. 11. In brief, we quantified the release of GHGs that would occur through the oxidation of stored organic material on clearing of the ecosystem and the annual GHG fluxes that would be displaced by clearing of the ecosystem (that is, net ecosystem exchange of CO₂, annual CH₄ uptake or release, annual N₂O release). We assumed minimal probability of major disturbances. Ecosystem–atmosphere GHG exchanges over T_E were translated into changes in atmospheric GHG concentrations and multiplied by the radiative efficiency of each GHG to obtain total radiative forcing from GHGs ($\Delta F_{\text{GHG}}^{T_E}$). Cumulative radiative forcing was translated into CO₂ equivalents over T_A. This is analogous to the commonly used approach for computing GHG global warming potentials²⁰, which typically use T_A = 100, but differs in that T_E > 1.

Biogeochemical and biophysical forcings were combined to calculate CRV:

$$CRV_{T_A}^{T_E} = \frac{\int_{t=0}^{T_A} \Delta E_{\text{eco}}^{T_E}(t) dt}{\int_{t=0}^{T_A} \Delta E_{\text{PCO}_2}(t) dt} \quad (1)$$

Here, $\Delta E_{\text{eco}}^{T_E}$ (nW m⁻² ha⁻¹ ecosystem yr⁻¹) is the change in surface energy, averaged globally (direct effects only), that would arise from biogeochemical and biophysical forcings over time span T_E following ecosystem clearing. For each year (t = 0 to T_E), $\Delta E_{\text{eco}}^{T_E}(t)$ was calculated as $\Delta E_{\text{GHG}}^{T_E} - \Delta R_n + \Delta LE$. ΔR_n and ΔLE were calculated by dividing the local changes to the energy balance by global surface area (5.1 × 10¹⁰ ha). ΔE_{PCO_2} (nW m⁻² yr⁻¹) is the extra radiative forcing that would arise from a pulse emission of CO₂ (1 Mg at t = 0).

Received 26 August 2011; accepted 24 November 2011;
published online 8 January 2012

References

- Bonan, G. B. Forests and climate change: Forcings, feedbacks, and the climate benefits of forests. *Science* **320**, 1444–1449 (2008).
- Chapin, F. I., Randerson, J., McGuire, A., Foley, J. & Field, C. Changing feedbacks in the climate–biosphere system. *Front. Ecol. Environ.* **6**, 313–320 (2008).
- UNFCCC Report on the Conference of the Parties on its Thirteenth Session, Held in Bali from 3 to 15 December 2007. Part Two: Action Taken by the Conference of the Parties at its Thirteenth Session 8–10 (United Nations, 2008).
- Anderson-Teixeira, K. J., Snyder, P. K. & DeLucia, E. H. Do biofuels life cycle analyses accurately quantify the climate impacts of biofuels-related land use change? *Illinois Law Rev.* **2011**, 589–622 (2011).
- Betts, R. A. Offset of the potential carbon sink from boreal forestation by decreases in surface albedo. *Nature* **408**, 187–190 (2000).
- Costa, M. H. & Foley, J. A. Combined effects of deforestation and doubled atmospheric CO₂ concentrations on the climate of Amazonia. *J. Clim.* **13**, 18–34 (2000).
- Jackson, R. B. *et al.* Protecting climate with forests. *Environ. Res. Lett.* **3**, 044006 (2008).
- Pielke, R. A. *et al.* The influence of land-use change and landscape dynamics on the climate system: Relevance to climate-change policy beyond the radiative effect of greenhouse gases. *Phil. Trans. R. Soc. Lond. A* **360**, 1705–1719 (2002).
- Betts, R. Implications of land ecosystem–atmosphere interactions for strategies for climate change adaptation and mitigation. *Tellus B* **59**, 602–615 (2007).
- Arora, V. K. & Montenegro, A. Small temperature benefits provided by realistic afforestation efforts. *Nature Geosci.* **4**, 514–518 (2011).
- Anderson-Teixeira, K. J. & DeLucia, E. H. The greenhouse gas value of ecosystems. *Glob. Change Biol.* **17**, 425–438 (2011).
- Gullison, R. E. *et al.* Tropical forests and climate policy. *Science* **316**, 985–986 (2007).

13. Betts, R. A. Climate science: Afforestation cools more or less. *Nature Geosci.* **4**, 504–505 (2011).
14. Loarie, S. R., Lobell, D. B., Asner, G. P., Mu, Q. & Field, C. B. Direct impacts on local climate of sugar-cane expansion in Brazil. *Nature Clim. Change* **1**, 105–109 (2011).
15. Georgescu, M., Lobell, D. B. & Field, C. B. Direct climate effects of perennial bioenergy crops in the United States. *Proc. Natl Acad. Sci. USA* **108**, 4307–4312 (2011).
16. Feddema, J. J. *et al.* The importance of land-cover change in simulating future climates. *Science* **310**, 1674–1678 (2005).
17. Albani, M., Medvigy, D., Hurtt, G. C. & Moorcroft, P. R. The contributions of land-use change, CO₂ fertilization, and climate variability to the Eastern US carbon sink. *Glob. Change Biol.* **12**, 2370–2390 (2006).
18. Pan, Y. *et al.* A large and persistent carbon sink in the world's forests. *Science* **333**, 988–993 (2011).
19. Herzog, T. *World Greenhouse Gas Emissions in 2005* WRI Working Paper (2009); available at <http://www.wri.org/publication/navigating-the-numbers>.
20. IPCC *Climate Change 2007: The Physical Science Basis* (eds. Solomon, S. *et al.*) (Cambridge Univ. Press, 2007).
21. West, P. C., Narisma, G. T., Barford, C. C., Kucharik, C. J. & Foley, J. A. An alternative approach for quantifying climate regulation by ecosystems. *Front. Ecol. Environ.* **9**, 126–133 (2011).
22. Snyder, P. K., Delire, C. & Foley, J. A. Evaluating the influence of different vegetation biomes on the global climate. *Clim. Dynam.* **23**, 279–302 (2004).
23. Twine, T. E., Kucharik, C. J. & Foley, J. A. Effects of land cover change on the energy and water balance of the Mississippi river basin. *J. Hydrometeorol.* **5**, 640–655 (2004).
24. Searchinger, T. *et al.* Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. *Science* **319**, 1238–1240 (2008).
25. Foley, J. A., Levis, S., Prentice, I. C., Pollard, D. & Thompson, S. L. Coupling dynamic models of climate and vegetation. *Glob. Change Biol.* **4**, 561–579 (1998).
26. Kucharik, C. J. Evaluation of a process-based agro-ecosystem model (Agro-IBIS) across the US Corn Belt: Simulations of the interannual variability in maize yield. *Earth Interact.* **7**, 1–33 (2003).
27. Vanloocke, A., Bernacchi, C. J. & Twine, T. E. The impacts of *Miscanthus × giganteus* production on the Midwest US hydrologic cycle. *GCB Bioenergy* **2**, 180–191 (2010).
28. Cuadra, S. V. *et al.* A biophysical model of sugarcane growth. *GCB Bioenergy* **4**, 36–48 (2012).
29. Kucharik, C. J. *et al.* Testing the performance of a dynamic global ecosystem model: Water balance, carbon balance, and vegetation structure. *Glob. Biogeochem. Cycles* **14**, 795–825 (2000).
30. Marland, G. *et al.* The climatic impacts of land surface change and carbon management, and the implications for climate-change mitigation policy. *Clim. Policy* **3**, 149–157 (2003).

Acknowledgements

This research was funded by the Energy Biosciences Institute and the BP Energy Sustainability Challenge Program. The authors acknowledge A. VanLoocke for his contributions to modelling biophysical factors for grasslands and crops.

Author contributions

K.J.A.-T., P.K.S. and E.H.D. conceived the experiment; K.J.A.-T., P.K.S., T.E.T., M.H.C. and S.V.C. contributed models; K.J.A.-T. compiled biogeochemical data and calculated GHGVs; P.K.S., T.E.T. and S.V.C. ran IBIS/AgroIBIS simulations; K.J.A.-T. and P.K.S. analysed data and prepared figures; K.J.A.-T. wrote the paper; all authors commented on the analysis and presentation of the data and revised the paper.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/natureclimatechange. Reprints and permissions information is available online at <http://www.nature.com/reprints>. Correspondence and requests for materials should be addressed to E.H.D.