GEOPHYSICAL RESEARCH LETTERS, VOL. 38, L15701, doi:10.1029/2011GL047848, 2011

Past land use decisions have increased mitigation potential of reforestation

J. Pongratz,[1] C. H. Reick,[2] T. Raddatz,[2] K. Caldeira,[1] and M. Claussen[2,3]

Received 18 April 2011; revised 22 June 2011; accepted 23 June 2011; published 2 August 2011.

[1] Anthropogenic land cover change (ALCC) influences global mean temperatures via counteracting effects: CO_2 emissions contribute to global warming, while biogeophysical effects, in particular the increase in surface albedo, often impose a cooling influence. Previous studies of idealized, large-scale deforestation found that albedo cooling dominates over CO_2 warming in boreal regions, indicating that boreal reforestation is not an effective mitigation tool. Here we show the importance of past land use decisions in influencing the mitigation potential of reforestation on these lands. In our simulations, CO_2 warming dominates over albedo cooling because past land use decisions resulted in the use of the most productive land with larger carbon stocks and less snow than on average. As a result past land use decisions extended CO_2 dominance to most agriculturally important regions in the world, suggesting that in most places reversion of past land cover change could contribute to climate change mitigation. While the relative magnitude of CO_2 and albedo effects remains uncertain, the historical land use pattern is found to be biased towards stronger CO_2 and weaker albedo effects as compared to idealized large-scale deforestation. **Citation:** Pongratz, J., C. H. Reick, T. Raddatz, K. Caldeira, and M. Claussen (2011), Past land use decisions have increased mitigation potential of reforestation, *Geophys. Res. Lett.*, *38*, L15701, doi:10.1029/2011GL047848.

1. Introduction

[2] More than one third of the Earth's land surface has undergone anthropogenic land cover change (ALCC) — the transformation from natural land cover to management, predominantly agriculture. This change in land cover influences climate through various processes: On the one hand, ALCC alters biogeochemical cycles, most notably causes CO_2 emissions from loss of standing biomass and soil carbon with deforestation [*Houghton et al.*, 1983; *Guo and Gifford*, 2002]. On the other hand, ALCC alters the biophysical properties of the land surface. Deforestation often reduces evapotranspiration because leaf area and rooting depth decrease. This can lead to surface warming in particular in the tropics [*Claussen et al.*, 2001]. A likely stronger effect on global mean temperature is, however, exerted by changes in surface albedo [*Betts*, 2001]. The albedo of forest is usually lower than that of agricultural land, so that deforestation typically leads to less solar radiation being absorbed at the surface [*Claussen et al.*, 2001]. This is especially true in the presence of snow, which is "masked" by forest. Exceptions include regions with dark soil that becomes exposed with deforestation. While there is no consensus on the overall sign of the global temperature response to global historical ALCC [see *Pongratz et al.*, 2010], studies agree on a substantial warming from the biogeochemical effects [*Denman et al.*, 2007], and usually a global cooling from biogeophysical effects, primarily driven by the increase in surface albedo [*Betts*, 2001].

[3] The studies cited above have focused on the climate response to global ALCC. But the amount of CO_2 emissions and the change in biophysical properties vary across regions and types of land cover change. Simulating the climate response to global ALCC does therefore not show how much a specific local occurrence of ALCC altered global mean climate.

[4] There are at least three reasons why it is important to know the contribution of local ALCC to global climate change. First, this information is necessary to attribute causes of past climate change. Second, agricultural expansion will continue in some of the regions of past ALCC, with similar climatic consequences. Third, forestation has been suggested as a tool to mitigate global warming because a growing forest takes up and stores carbon from the atmosphere [*UNFCCC*, 2005]. *Betts* [2000] and *Claussen et al.* [2001] have, however, concluded that in boreal regions warming caused by the reduction in surface albedo could dominate over the CO_2 uptake, i.e., the magnitude of the positive albedo forcing following forestation could be larger than the magnitude of the negative forcing from CO_2 uptake. This conclusion has subsequently been supported by further large-scale forestation/deforestation model experiments [*Sitch et al.*, 2005; *Bala et al.*, 2007; *Bathiany et al.*, 2010]. Under the constraints imposed by climate and the availability of area, a reversal of past ALCC may often be the most feasible step of implementing ALCC as mitigation tool. While a detailed analysis is needed for specific reforestation projects, the climate effect of past ALCC is likely to be a good indicator of the mitigation potential of reversing the area to its natural state.

2. Methods

[5] In this study, we quantify the contribution of local ALCC (Figure 1) to historical global warming. The ALCC reconstruction applied here considers permanent changes in land cover as caused by changes in agricultural area [*Pongratz et al.*, 2008] and therefore includes land cleared of forest in the past that potentially could be reforested in the future. To localize and compare biogeophysical and biogeochemical effects on climate we calculate radiative forcing (RF) [*Hansen et al.*, 1997], following the approach by *Betts* [2000]. From transient climate simulations with the comprehensive

---

[1] Department of Global Ecology, Carnegie Institution, Stanford, California, USA.
[2] Max Planck Institute for Meteorology, Hamburg, Germany.
[3] KlimaCampus, University of Hamburg, Hamburg, Germany.

0094-8276/11/2011GL047848

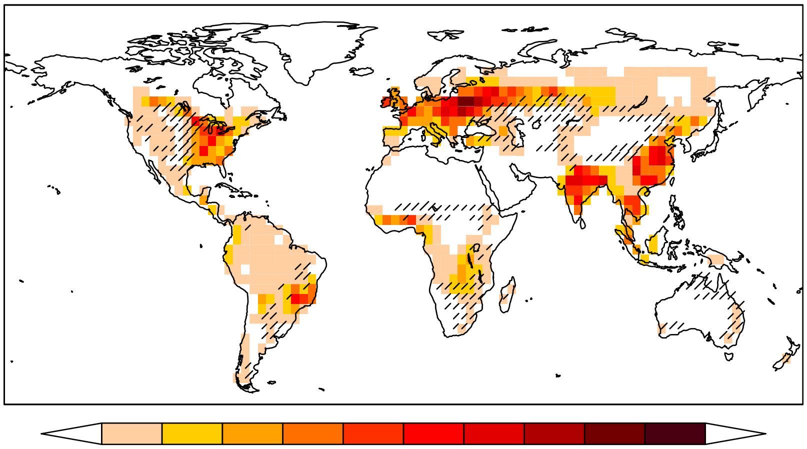

Figure 1. Change in natural vegetation cover due to agricultural expansion AD 800 to 1992. Solid colors indicate decrease in forest cover (fraction of grid cell), hatching indicates regions where on more than 40% of the grid cell natural grass- and shrubland has been converted to agriculture.

climate-carbon cycle model ECHAM5-JSBACH/MPIOM-HAMOCC5 we determine the increase in atmospheric CO_2 caused by ALCC and quantify the contribution of each individual grid cell to this CO_2 increase. We then compare the RF associated with the increase in CO_2 to the one from effects of surface albedo changes on radiative fluxes at the tropopause (for details, see auxiliary material).[1] Snow cover and other climate variables have been evaluated and found to be in range of observations and other models [*Friedlingstein et al.*, 2006; *Randall et al.*, 2007]. We have shown in previous publications [*Pongratz et al.*, 2009a, 2009b] that our estimates of albedo RF and of CO_2 emissions are within the range of independent estimates. The time period covers the last millennium (AD 800 to 1992) and therefore much of the human impact on the climate system over the agricultural era [*Pongratz et al.*, 2009a, 2009b].

3. Results

[6] The change in radiative forcing (RF) from surface albedo changes (Figure 2a) has a global mean value of -0.20 W/m^2. The albedo RF has strongly negative values (i.e., cooling influence) in Central and East Europe, where the greatest deforestation occurs, and in the tropical and subtropical regions, where a large albedo increase coincides with high insolation. Small positive values emerge over dark soils exposed by deforestation (e.g., central Asia) or bright soils more continuously covered by vegetation under management (e.g., Sahel). Figure 2b depicts the mostly positive RF from CO_2 emissions since AD 800. Its global mean is 0.35 W/m^2 caused by an atmospheric CO_2 increase of 19 ppm. Strongly positive RF (i.e., warming influence) is caused by deforestation in Europe and North America due to the large amounts of land area converted, but also by deforestation in the tropics and subtropics due to the large loss of standing biomass. The CO_2 RF and albedo RF sum to a global total RF value of 0.15 W/m^2. The regions with the most intense large-scale cultivation worldwide — Europe, India, China, and Eastern North America — and regions with tropical forest have a positive total RF in our simulations (Figure 2c). Smaller areas of negative RF are simulated in the western U.S., subtropical regions, Australia, and central south Asia, often agriculturally more marginal regions where grasslands and shrublands are used for pasture.

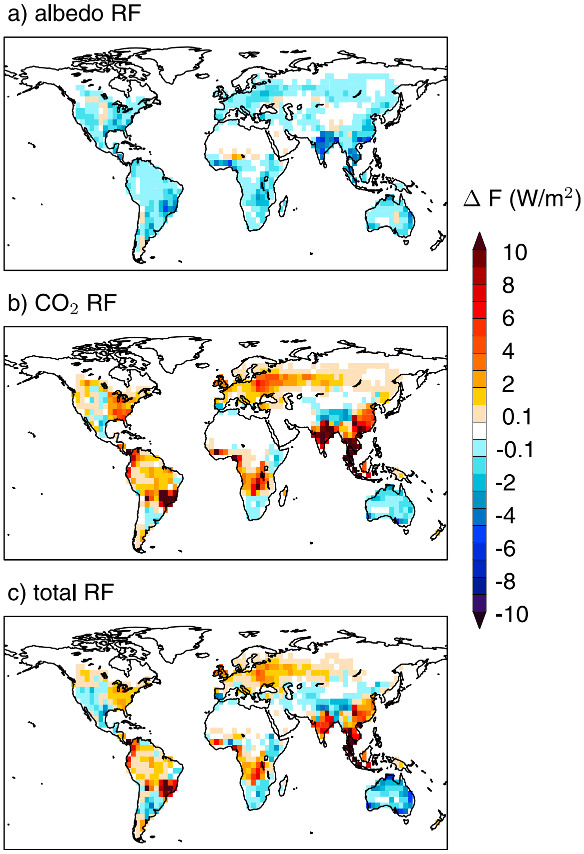

Figure 2. Changes in radiative forcing (RF), ΔF, AD 800 to 1992. (a) RF from ALCC-induced surface albedo changes; (b) RF from ALCC-induced CO_2 emissions; (c) total RF as sum of Figures 2a and 2b.

---

[1] Auxiliary materials are available in the HTML. doi:10.1029/2011GL047848.

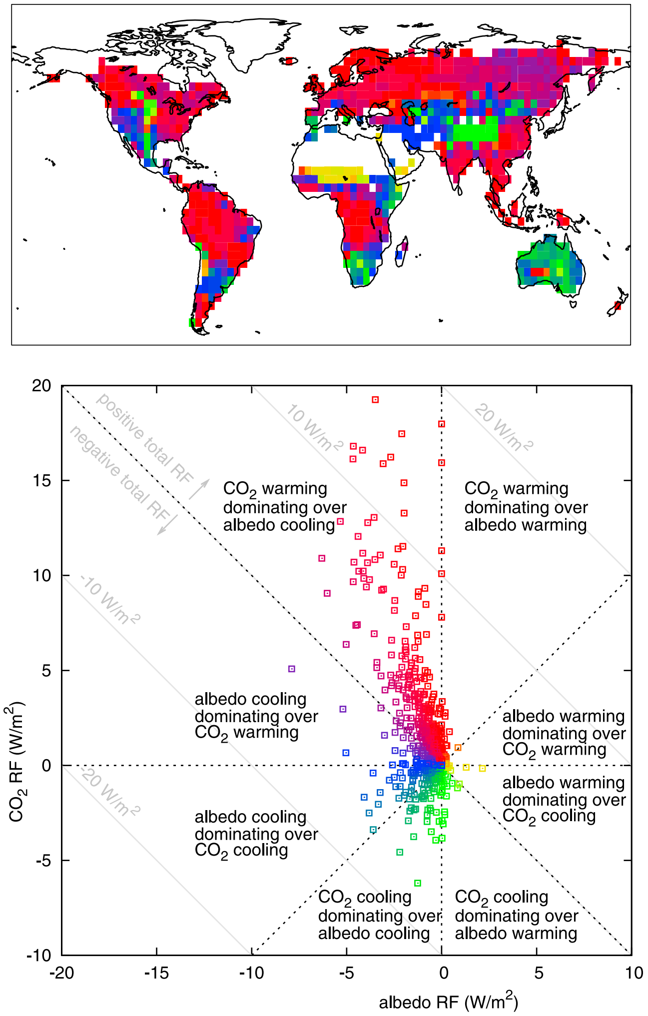

Figure 3. Relative importance of CO_2 and surface albedo radiative forcing (RF). The scatter plot shows changes in CO_2 and albedo RF for each grid point in which ALCC occurs. The colors correspond to the angular direction and therefore encode the ratio of CO_2 RF over albedo RF. The map shows the spatial location of the grid points and their corresponding ratio of CO_2 RF and albedo RF, using the color scheme of the scatter plot.

[7] The relative importance of CO_2 and albedo in causing a positive or negative total RF in our model is detailed in Figure 3. ALCC has had a warming influence in the majority of places. Positive CO_2 RF dominates over negative albedo RF over about half of Earth's land surface; these areas include the regions of strongest total RF from ALCC. Total RF from ALCC in many snowy boreal regions is indeed negative and albedo-dominated, but these tend to be areas with little agriculture and thus have small total RF. Outside the boreal regions, a dominance of albedo cooling over CO_2 warming is simulated in locations such as parts of the western U.S., often because a strong albedo increase due to bright soils coincides with low emissions from grassland and shrubland conversion. In some locations an increase in carbon stocks and an increase in albedo both act as cooling influence. In parts of Australia, the carbon uptake with transformation of natural vegetation is likely a model artifact caused by the description of all grazing land as pasture (grassland) in JSBACH, which can lead to CO_2 uptake as pasture can accumulate high amounts of soil organic carbon [*Guo and Gifford*, 2002]; in reality the existing shrublands are often grazed but not converted to grassland.

4. Discussion

[8] The historical analysis presented here approximates the likely global climate impact of continuing deforestation, such as tropical deforestation. Currently, rates of net deforestation are highest in the tropics, regions in which, in our analysis, effects of CO_2 clearly dominate. Our regional assessment is consistent with previous simulations suggesting global warming from idealized large-scale tropical deforestation [*Claussen et al.*, 2001; *Bala et al.*, 2007], but also shows substantial spatial heterogeneity in the relative importance of CO_2 emissions and surface albedo aspects (Figure 3).

[9] The dominance of CO_2 over albedo forcing simulated in our model applies to most areas with ALCC in the northern temperate and boreal regions. This contrasts with the conclusions of previous studies that albedo effects dominate in these regions [*Betts*, 2000; *Claussen et al.*, 2001; *Sitch et al.*, 2005; *Bala et al.*, 2007; *Bathiany et al.*, 2010]. The reason for the apparent discrepancy to previous modeling studies lies in the assumption of the underlying land cover change. In these largely idealized studies whole latitude bands of homogeneous forest cover were completely replaced by grasslands. However, land cover change in the past occurred preferentially in places that were more suitable for agriculture: Overall, past land use decisions resulted in high CO_2 emissions due to the conversion of productive locations where natural vegetation produced above-average carbon stocks (Figure 4a). Furthermore, within a vegetation zone, past land use decision overall resulted in the use of areas with below-average snow cover (Figure 4b), so that the albedo change resulting from deforestation was smaller than would occur under mean snow conditions.

[10] We identify a statistically significant pattern of historical land cover change where, in the temperate and boreal regions, model grid cells representing areas with strong deforestation exhibit on average (individual locations may

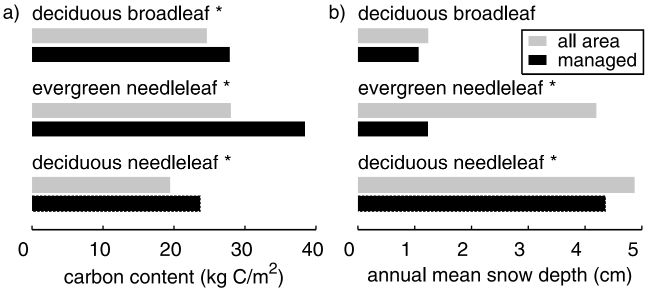

Figure 4. Difference in climate-relevant properties of natural versus managed areas. (a) Total carbon stock and (b) annual mean snow depth of the temperate/boreal vegetation types in our simulations averaged over the entire area in AD 800 (gray bars) or only the area subsequently transformed to agricultural use (black bars). Asterisks indicate differences between means of entire and used areas that are significant on the 95% level of a weighted two sample t-test.

differ) a stronger CO_2 RF per m^2 of deforestation and a weaker albedo RF per m^2 of deforestation than a random choice of land (Figure S3 in the auxiliary material). Although a choice by farmers to cultivate on average more highly productive area with less snow cover may be plausible from an individual point of view, it is beyond the scope of this study to identify how various historical and socioeconomic factors influenced land use decisions. However, a consequence of these non-random land use decisions is a bias towards stronger CO_2 and weaker albedo effects. Thus, a reversal of past patterns of land cover change could produce a substantially different result for the overall climate response than would be obtained for idealized large-scale reforestation.

[11] When the present climate state is used to infer to the future [e.g., *Betts*, 2000], a reversal of historical ALCC should be comparable in magnitude to Figure 2c, but of opposite sign. The bias towards stronger CO_2 and weaker albedo effects then implies that the mitigation potential of reforestation is underestimated when based on an idealized large-scale ALCC pattern as compared to the historical pattern. In our simulations, the overall climate response would be a net cooling influence, indicating that reforestation even in high to midlatitudes could be an effective mitigation tool. Detailed estimates of the effect of future ALCC, however, depend on the specific climate and ALCC scenarios assumed, because the RF of future ALCC will depend on the future evolution of the climate system. For a future reversion of ALCC, the scale of ALCC will influence the partitioning of CO_2 between atmosphere, ocean, and land. Further, future climate change will influence carbon stocks and surface albedo, e.g., receding snow cover will likely diminish the warming influence of albedo effects with reforestation in the future.

[12] The relative magnitude of CO_2 and albedo effects and the sign of the net effect may depend on model parameterization; in particular albedo effects have been shown to vary across models [*Pitman et al.*, 2009]. Model parameterizations are generally dependent on vegetation type rather than geographic location. The bias introduced by the historical ALCC pattern and identified in Figure 4 separately for each relevant vegetation type is determined by large-scale climate variations and thus not strongly affected by model specificities. The same model that we used in our study has been used by *Bathiany et al.* [2010] with idealized large-scale de/afforestation, where it supported the previous studies' conclusion of an albedo over CO_2 dominance in the boreal region. This shows that the same model can lead to the opposite sign of the climate response depending on whether the land cover change follows an idealized large-scale or the realistic historical pattern. The mitigation potential of reforestation projects (i.e., reversal of past ALCC) may substantially differ from that determined for idealized large-scale ALCC simulations.

[13] A CO_2 dominance for afforestation in the boreal region has been suggested by a satellite-based study [*Montenegro et al.*, 2009], which assigned carbon stocks by vegetation type assuming values for boreal forest that were greater than simulated by most biosphere models. Our model predicts variations in carbon stocks within vegetation types with mean values consistent with most other assessments, for boreal forest of 5.5 kg C/m^2 as compared with 4.2–6.4 kg C/m^2 summarized in the IPCC TAR [*Prentice et al.*, 2001]. In contrast to *Montenegro et al.* [2009], we conclude that a primary reason for the boreal CO_2 dominance is the farmers' choice in the past to use regions with high carbon stocks, and not that previous model studies [*Betts*, 2000; *Claussen et al.*, 2001; *Sitch et al.*, 2005; *Bala et al.*, 2007; *Bathiany et al.*, 2010] have underestimated mean boreal forest carbon stocks.

[14] The ALCC reconstruction applied here considers changes in natural vegetation cover as caused by expansion and abandonment of agricultural area, neglecting land management effects such as wood harvest. Such management effects usually represents a type of land management that does not lead to a permanent change in type of land cover. Because our study investigates the effect of reversion to the natural vegetation type, only areas that have undergone a permanent change in type of land cover in the past, e.g., from forest to non-forest, are considered. Our study further does not consider effects of displacement, i.e., that reforestation in one region shifts demand for agricultural area, and thus possibly deforestation, to another region [*Meyfroidt et al.*, 2010]; displacement could potentially counteract the mitigation effect of reforestation. However, socioeconomic drivers of land cover change are beyond the scope of our physical study, which investigates the effect of reversing managed land to its natural state independent of the underlying reason for abandonment. A caveat of our study is the use of one specific reconstruction of historical land cover changes, which are only known with some uncertainty. However, Figure 3 shows that the net radiative forcing from land-cover change changes at the scale of regions but produces relatively consistent results within regions. Thus, errors in locating the site of deforestation within a region are unlikely to substantially change results.

[15] The albedo effect is the dominant biogeophysical effect on the global scale [*Betts*, 2001]. Still, focusing only on surface albedo changes neglects a range of other biogeophysical effects of ALCC [*Pielke et al.*, 2002]. ALCC alters evapotranspiration, which is reduced particularly by deforestation. This leads to less water vapor in the atmosphere and a negative RF, which however has a substantially smaller magnitude than the negative albedo RF [*Davin et al.*, 2007]. Moreover, the resulting cooling is counteracted by mechanisms that warm the surface, namely less evaporative cooling at the surface and a reduction in cloud cover associated with reduced evapotranspiration, as found in particular in the tropics [*Claussen et al.*, 2001]. Because these effects tend to act in the same direction as the CO_2 RF, namely warming, the albedo effect likely constitutes an upper estimate of the cooling effect of biogeophysical changes, supporting our conclusion of a dominance of CO_2 warming over biogeophysical effects. The complete picture of biogeophysical effects can be derived from coupled simulations for a given future scenario of ALCC and climate, but the impact cannot be easily attributed to a specific location of ALCC. For this reason and because the approach of comparing CO_2 and albedo effects is consistent with previous studies [*Betts*, 2000], we restrict our quantitative analysis of biogeophysical effects to albedo.

5. Conclusion

[16] Previous studies of idealized, large-scale deforestation found that albedo cooling dominates over CO_2 warming in boreal regions, indicating that boreal reforestation would be counter-productive as mitigation tool. Here we show the importance of using historical reconstructions of land cover change to estimating the mitigation potential of reforestation.

In our simulations, most regions of intensive ALCC have contributed a positive forcing to global climate change because CO_2 warming dominated over albedo cooling. Past land use decisions in temperate and boreal regions resulted in the use of land that was more productive with larger carbon stocks and less snow than on average. As a result, in our model, past land use decisions extended CO_2 dominance to most agriculturally important regions in the world, suggesting that in most places reversion of past land cover change could contribute to climate change mitigation. While the relative magnitude of CO_2 and albedo effects at an individual location remains uncertain and dependent on model parameters, the historical land use pattern in temperate and boreal regions is likely biased towards stronger CO_2 and weaker albedo effects as compared to idealized large-scale deforestation. This shows the importance of geographically specific analysis for predicting effects of future land cover change in these areas, both for continued deforestation and a reversion to the natural state.

[17] **Acknowledgments.** The transient simulations for this study were carried out as part of the "Community Simulations of the Last Millennium" (http://www.mpimet.mpg.de/en/wissenschaft/working-groups/millennium.html); we would like to thank all participants.

[18] The Editor thanks two anonymous reviewers for their assistance in evaluating this paper.

References

Bala, G., K. Caldeira, M. Wickett, T. J. Phillips, D. B. Lobell, C. Delire, and A. Mirin (2007), Combined climate and carbon-cycle effects of large-scale deforestation, *Proc. Natl. Acad. Sci. U. S. A.*, *104*(16), 6550–6555.

Bathiany, S., M. Claussen, V. Brovkin, T. Raddatz, and V. Gayler (2010), Combined biogeophysical and biogeochemical effects of large-scale forest cover changes in the MPI Earth system model, *Biogeosciences*, *7*, 1383–1399, doi:10.5194/bg-7-1383-2010.

Betts, R. A. (2000), Offset of the potential carbon sink from boreal forestation by decreases in surface albedo, *Nature*, *408*, 187–190.

Betts, R. A. (2001), Biogeophysical impacts of land use on present-day climate: Near-surface temperature change and radiative forcing, *Atmos. Sci. Lett.*, *1*, 39–51, doi:10.1006/asle.2001.0023.

Claussen, M., V. Brovkin, and A. Ganopolski (2001), Biogeophysical versus biogeochemical feedbacks of large-scale land cover change, *Geophys. Res. Lett.*, *28*(6), 1011–1014, doi:10.1029/2000GL012471.

Davin, E. L., N. de Noblet-Ducoudré, and P. Friedlingstein (2007), Impact of land cover change on surface climate: Relevance of the radiative forcing concept, *Geophys. Res. Lett.*, *34*, L13702, doi:10.1029/2007GL029678.

Denman, K. L., et al. (2007), Couplings between changes in the climate system and biogeochemistry, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., pp. 499–587, Cambridge Univ. Press, Cambridge, U. K.

Friedlingstein, P., et al. (2006), Climate-carbon cycle feedback analysis: Results from the C4MIP model intercomparison, *J. Clim.*, *19*, 3337–3353.

Guo, L. B., and R. M. Gifford (2002), Soil carbon stocks and land use change: A meta analysis, *Global Change Biol.*, *8*, 345–360.

Hansen, J., M. Sato, and R. Ruedy (1997), Radiative forcing and climate response, *J. Geophys. Res.*, *102*(D6), 6831–6864, doi:10.1029/96JD03436.

Houghton, R. A., J. E. Hobbie, J. M. Melillo, B. Moore, B. J. Peterson, G. R. Shaver, and G. M. Woodwell (1983), Changes in the carbon content of terrestrial biota and soils between 1860 and 1980: A net release of CO_2 to the atmosphere, *Ecol. Monogr.*, *53*(3), 235–262.

Meyfroidt, P., T. K. Rudel, and E. F. Lambin (2010), Forest transitions, trade, and the global displacement of land use, *Proc. Natl. Acad. Sci. U. S. A.*, *107*(49), 20,917–20,922.

Montenegro, A., M. Eby, Q. Mu, M. Mulligan, A. J. Weaver, E. C. Wiebe, and M. Zhao (2009), The net carbon drawdown of small scale afforestation from satellite observations, *Global Planet. Change*, *69*, 195–204.

Pielke, R. A., Sr., G. Marland, R. A. Betts, T. N. Chase, J. L. Eastman, J. O. Niles, D. D. S. Niyogi, and S. W. Running (2002), 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, *Philos. Trans. R. Soc. A*, *360*, 1705–1719.

Pitman, A. J., et al. (2009), Uncertainties in climate responses to past land cover change: First results from the LUCID intercomparison study, *Geophys. Res. Lett.*, *36*, L14814, doi:10.1029/2009GL039076.

Pongratz, J., C. Reick, T. Raddatz, and M. Claussen (2008), A reconstruction of global agricultural areas and land cover for the last millennium, *Global Biogeochem. Cycles*, *22*, GB3018, doi:10.1029/2007GB003153.

Pongratz, J., T. Raddatz, C. H. Reick, M. Esch, and M. Claussen (2009a), Radiative forcing from anthropogenic land cover change since A.D. 800, *Geophys. Res. Lett.*, *36*, L02709, doi:10.1029/2008GL036394.

Pongratz, J., C. H. Reick, T. Raddatz, and M. Claussen (2009b), Effects of anthropogenic land cover change on the carbon cycle of the last millennium, *Global Biogeochem. Cycles*, *23*, GB4001, doi:10.1029/2009GB003488.

Pongratz, J., C. H. Reick, T. Raddatz, and M. Claussen (2010), Biogeophysical versus biogeochemical climate response to historical anthropogenic land cover change, *Geophys. Res. Lett.*, *37*, L08702, doi:10.1029/2010GL043010.

Prentice, I. C., et al. (2001), The carbon cycle and atmospheric carbon dioxide, in *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, edited by J. T. Houghton et al., pp. 183–237, Cambridge Univ. Press, Cambridge, U. K.

Randall, D. A., et al. (2007), Climate models and their evaluation, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al., pp. 589–662, Cambridge Univ. Press, Cambridge, U. K.

Sitch, S., V. Brovkin, W. von Bloh, D. van Vuuren, B. Eickhout, and A. Ganopolski (2005), Impacts of future land cover changes on atmospheric CO_2 and climate, *Global Biogeochem. Cycles*, *19*, GB2013, doi:10.1029/2004GB002311.

United Nations Framework Convention on Climate Change (UNFCCC) (2005), Reducing emissions from deforestation in developing countries: approaches to stimulate action, United Nations Office at Geneva, Geneva, Switzerland. (also available at http://www.unfccc.int/resource/docs/2005/cop11/eng/misc01.pdf)

K. Caldeira and J. Pongratz, Department of Global Ecology, Carnegie Institution, 260 Panama St., Stanford, CA 94305, USA. (pongratz@carnegie.stanford.edu)

M. Claussen, T. Raddatz, and C. H. Reick, Max Planck Institute for Meteorology, Bundesstr. 53, D-20146 Hamburg, Germany.