Combined climate and carbon-cycle effects of large-scale deforestation

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The prevention of deforestation and promotion of afforestation have often been cited as strategies to slow global warming. Deforestation releases CO_2 to the atmosphere, which exerts a warming influence on Earth's climate. However, biophysical effects of deforestation, which include changes in land surface albedo, evapotranspiration, and cloud cover also affect climate. Here we present results from several large-scale deforestation experiments performed with a three-dimensional coupled global carbon-cycle and climate model. These simulations were performed by using a fully three-dimensional model representing physical and biogeochemical interactions among land, atmosphere, and ocean. We find that global-scale deforestation has a net cooling influence on Earth's climate, because the warming carbon-cycle effects of deforestation are overwhelmed by the net cooling associated with changes in albedo and evapotranspiration. Latitude-specific deforestation experiments indicate that afforestation projects in the tropics would be clearly beneficial in mitigating global-scale warming, but would be counterproductive if implemented at high latitudes and would offer only marginal benefits in temperate regions. Although these results question the efficacy of mid- and high-latitude afforestation projects for climate mitigation, forests remain environmentally valuable resources for many reasons unrelated to climate.

afforestation | albedo change | climate change | global warming | climate policy

Deforestation affects the global climate both by releasing the carbon stored in the living plants and soils, and by altering the physical properties of the planetary surface. Deforestation exerts a warming influence by (*i*) adding CO_2 to the atmosphere, (*ii*) eliminating the possible increased carbon storage in trees as a result of future CO_2 fertilization, and (*iii*) decreasing evapotranspiration, particularly in the tropics (1–6). However, deforestation also exerts a cooling influence by (*iv*) decreasing the surface albedo, particularly in seasonally snow-covered high latitudes (7–10). We will refer to the first two climate effects that are mediated by changes in atmospheric carbon dioxide content as "carbon-cycle effects" and refer to the other two climate effects of forests as "biophysical effects."

Because CO_2 is well mixed in the atmosphere, carbon-cycle effects are manifested globally, but biophysical effects are most strongly felt at regional scales. Although the carbon-cycle effects have been taken into account in the promotion of afforestation as a climate change mitigation strategy, the biophysical effects of land-cover change have been largely ignored (11). The investigation of the combined carbon-cycle and climate effects of deforestation on the global climate is the subject of this paper.

The relative importance of carbon-cycle and albedo effects can be quantified in terms of radiative forcing (7), but the complexity of the climate response to changes in hydrological cycle challenges the application of such a metric (12) to changes in evapotranspiration. Evapotranspiration changes trigger atmospheric water vapor, cloud, and lapse-rate changes that produce local and global temperature changes. Previous studies have shown that deforestation in the tropics would decrease evapotranspiration rates and increase sensible heat fluxes, resulting in regionally decreased precipitation and increased surface temperature (1–3, 5, 13, 14).

Past studies have investigated the biophysical effects of deforestation in specific climatic zones (1–5, 8, 13, 15), of global deforestation (16–19), and the combined biophysical and carbon-cycle effects of deforestation at different latitudes by using simple models (7, 20–22). Here, we employ the Lawrence Livermore National Laboratory INCCA (Integrated Climate and Carbon) model (23, 24) to investigate transient carbon/climate interactions from year 2000 to 2150. Our study investigates the combined climate and carbon-cycle effects of deforestation in a fully interactive three-dimensional climate model that incorporates complex submodels of vegetation dynamics and terrestrial and oceanic components of the carbon cycle (23–25).

Results

Atmospheric CO_2 content is greater in the Global deforestation experiment by 381 ppmv because of both the release of carbon stored in trees in the early 21st century and the loss of CO_2 fertilization of forested ecosystems seen in the Standard simulation (Fig. 1). Despite higher atmospheric CO_2 concentrations, the global- and annual-mean temperature in the Global case is cooler by $\approx$0.3 K than the Standard case. Thus, on a global-mean basis, the warming carbon-cycle effects of deforestation are overwhelmed by the cooling biophysical effects.

Relative to the Standard case, the atmospheric CO_2 concentration is higher by 299, 110, and 5 ppmv in the Tropical, Temperate, and Boreal cases. The global-mean temperature differences relative to the Standard case in year 2100 in the Tropical, Temperate, and Boreal experiments are $+0.7$ K, -0.04 K, and -0.8 K, respectively (Fig. 1), implying that the combined carbon-cycle and biophysical effects from tropical, temperate, and boreal deforestation are, respectively, net warming, near-zero temperature change, and net cooling. These latitude-band experiments thus suggest that projects in the tropics promoting afforestation are likely to slow down global warming, but such projects would offer only little to no climate benefits when implemented in temperate regions and would be counterproductive, from a climate-perspective, at higher latitudes.

The linear sum of the area-weighted global-mean temperature change over all of the latitude-band experiments is -0.1 K in the year 2100. This value is close to the corresponding -0.3 K temperature change of the Global deforestation simulation,

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Abbreviation: INCCA, Integrated Climate and Carbon.

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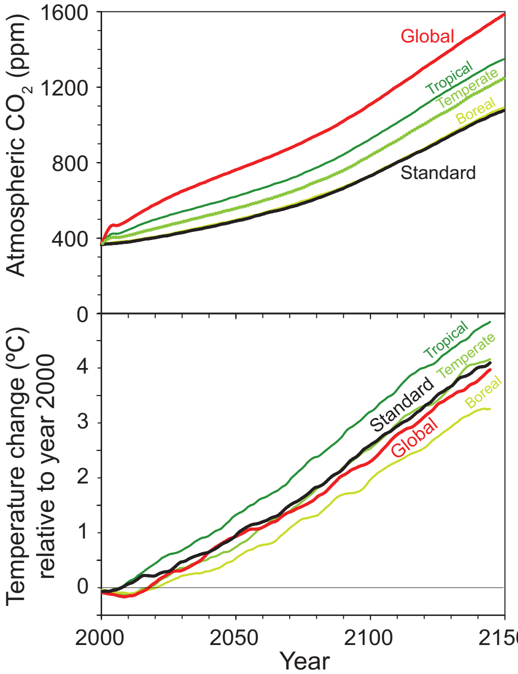

Fig. 1. Simulated temporal evolution of atmospheric CO_2 (*Upper*) and 10-year running mean of surface temperature change (*Lower*) for the period 2000–2150 in the Standard and deforestation experiments. Warming effects of increased atmospheric CO_2 are more than offset by the cooling biophysical effects of global deforestation in the Global case, producing a cooling relative to the Standard experiment of ≈0.3 K around year 2100. The combined carbon-cycle and biophysical effects from Tropical, Temperate, and Boreal deforestation are net cooling, near-zero temperature change, and net warming, respectively. The sum of the temperature changes in the latitude-band experiments is approximately equal to the temperature change in the Global case, suggesting near-linearity.

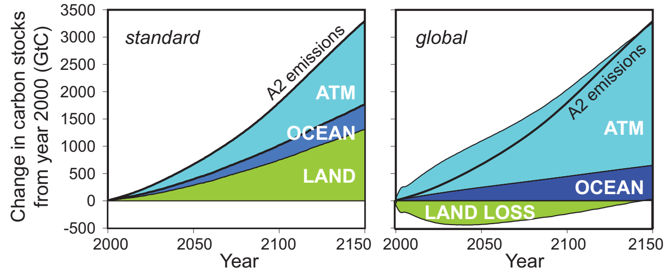

Fig. 2. Simulated cumulative emissions and carbon stock changes in atmosphere, ocean, and land for the period 2000–2150 in Standard (*A*) and Global (*B*) deforestation experiments. In Standard, strong CO_2 fertilization results in vigorous uptake and storage of carbon by land ecosystems. In the Global case, land ecosystem carbon is lost to the atmosphere as a result of global deforestation. Most of this carbon is ultimately reabsorbed by grasses and shrubs growing in a warmer CO_2-fertilized climate at year 2100. Of the land ecosystem carbon in the Standard simulation that is not present in the land biosphere in the Global case at year 2100, 82% resides in the atmosphere and the remaining 18% in the oceans.

suggesting a near-linear behavior of the large-scale climate system despite the many nonlinear processes represented by the INCCA model. The linear sum is slightly larger because, in the latitude-band experiments, our dynamic vegetation model allows the forests to expand in the regions that are not deforested (23, 26), and forests have lower albedo and absorb more solar radiation than grasses. The presence of trees in the latitude-band deforestation experiments and the consequent higher CO_2 fertilization causes the linear sum of CO_2 changes from the Tropical, Temperate, and Boreal experiments to be lower than that of the Global case by 67 ppmv in year 2100.

Because the linear sum of the temperature response from latitude-band experiments is approximately equal to that of the Global case (Fig. 1), we focus our analysis on our global-scale deforestation simulation for brevity. The removal of forests in the Global case results in an atmospheric CO_2 concentration at year 2100 that is 381 ppmv greater than in the Standard simulation (1,113 vs. 732 ppmv; Fig. 1). In the Standard A2 scenario, 1,790 PgC carbon is emitted to the atmosphere over the 21st century (Fig. 2). By year 2100, the terrestrial biosphere in the Global deforestation experiment has 972 Pg less carbon than in the Standard case. Approximately 82% (799 PgC) of this carbon resides in the atmosphere, with the oceans taking up the remaining 18% (173 PgC). The ocean uptake increases in the Global case (444 vs. 271 PgC in Standard) because the higher atmospheric CO_2 concentration drives an increased flux of carbon into the oceans.

The spatial distribution of climate and carbon-cycle changes in the Global case for the decade centered on year 2100 is shown in Fig. 3*A*. Similar to the global-mean statistics, the linear sum (Fig. 3*B*) of the spatial pattern of temperature response from the latitude-specific Boreal, Temperate, and Tropical deforestation experiments (Fig. 3 *C*–*E*) is also approximately equal to that of the Global case (Fig. 3*A*). This finding once again highlights the apparent linear response of the large-scale climate system despite the presence of many nonlinear processes.

The spatial pattern of temperature differences suggests that the strongest cooling in the Global case is associated with the removal of boreal forests in the Northern Hemisphere high latitudes (Fig. 3*A* and Table 1). The replacement of these forests by grasses and shrubs increases the surface albedo (brightens the surface) by as much as 0.25 (Fig. 4*A*). This results in decreased absorption of surface solar radiation and cooling that exceeds 6 K in some locations, despite higher CO_2 concentrations and high-latitude amplification of CO_2-induced warming (27). The albedo effect therefore dominates the climate response in the Northern Hemisphere mid-latitudes and high-latitudes. However, the magnitude of cooling due to albedo change would likely become smaller after 2100 as the length of the snow season is reduced further; we noted a slight decrease in the surface albedo over boreal region during the period 2010–2100.

In the tropics, however, increases in surface albedo (Fig. 4*A* and Table 1) do not produce as much cooling, largely due to the changes in clouds. The removal of forests also decreases evapotranspiration (Fig. 4*B*), resulting in a decrease of clouds (Fig. 4*C*). Thus, the replacement of tropical forests with grasslands and shrublands brightens the surface, but the decrease of clouds tends to darken the planet. These effects nearly cancel each other so that the planetary albedo at the top of the atmosphere (Fig. 4*D*) changes little over tropical regions. This observation suggests that cloud feedbacks initiated by evapotranspiration changes play a major role in determining the overall climatic impact of deforestation in the tropics.

Despite higher atmosphere CO_2 concentrations, the average annual-mean surface temperature over land in the Global deforestation experiment is cooler by 2.1 K, 1.6 K, and 0.4 K than that of the Standard experiment in the Northern Hemisphere high latitudes (50°N to 90°N), mid-latitudes (20°N to 50°N), and tropics (20°S to 20°N), respectively (Table 1). In contrast, the Southern Hemisphere mid-latitude (50°S to 20°S) land surface warms by 0.1 K. In the Northern Hemisphere mid-latitudes and high latitudes, surface albedo effects dominate, resulting in decreased net surface solar absorption and cooling. In the tropics and Southern Hemisphere mid-latitudes, the surface albedo decrease is comparable with that in the Northern Hemisphere mid-latitudes (Table 1), but the decreases in evapotranspiration and cloudiness lead to increases in the surface incident and absorbed solar radiation that tend to warm the surface. However, the net biophysical effect is still cooling, and it is larger than the warming carbon-cycle effects in the tropics, while being only slightly smaller in the Southern Hemisphere mid-latitudes (Fig. 3*A*).

The annual- and seasonal-mean changes in surface albedo and evapotranspiration rates in areas covered by specific vegetation types are shown in supporting information (SI) Tables 3 and 4. These tables reveal large albedo changes in boreal forests in the winter and evapotranspiration changes in all tree-type vegetation during summer. Because convection plays an important role in vertical moisture transport and cloud formation, the evapotranspiration changes result in reduction in cloudiness (Table 1).

Analysis of the latitude-band deforestation experiments shows large surface albedo changes in the latitudes where deforestation takes place, with the largest changes in boreal regions (SI Fig. 5). The albedo changes are larger in the winter hemispheres. The evapotranspiration changes are larger in the deforested tropical and temperate regions and in the summer hemispheres. However, planetary changes in albedo are restricted to deforested boreal areas. Tropical deforestation warms the planet everywhere (Table 2), indicating that the remote warming from the carbon-cycle (greenhouse) effect dominates in this case. Even though the evapotranspiration changes tend to enhance the local warming, the change in surface albedo tends to reduce the local warming to less than the global average in our model. Temperate deforestation produces local cooling due to dominant albedo change and remote warming due to carbon-cycle effect; these effects cancel each other on a global-mean basis. Boreal deforestation, in addition to causing strong local cooling, produces cooling everywhere, suggesting remote cooling effects through circulation (28–31).

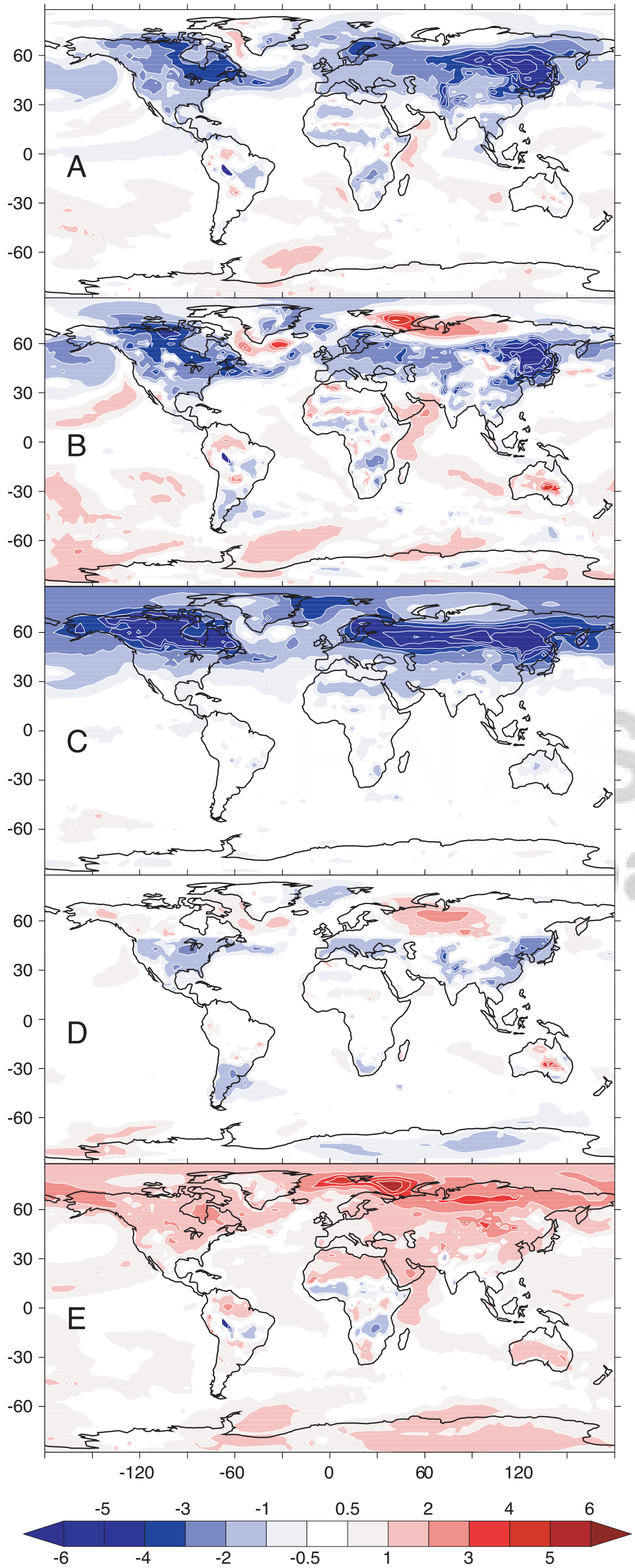

Fig. 3. Simulated spatial surface temperature differences relative to the Standard experiment in the decade centered on year 2100 for the Global (*A*) and linear sum (*B*) of Boreal (*C*), Temperate (*D*), and Tropical (*E*) deforestation experiments. Cooling biophysical effects of deforestation overwhelm warming carbon-cycle effects over most of the land surface (including tropical regions), but are most pronounced in the Northern high latitudes. Comparison of *A* and *B* shows the near-linear behavior of the model climate system. Cooling biophysical effects of deforestation dominate the climate response in the Boreal deforestation case (*C*). In the Temperate deforestation case (*D*), there are strong local cooling responses, although the global-mean response is near zero. The carbon-cycle effects of warming overwhelm the biophysical effects in the Tropical deforestation case (*E*) with slight local cooling responses from the biophysical effects.

Discussion

The approximate global-mean warming from carbon-cycle effects and cooling from biophysical effects can be estimated from our model's known climate sensitivity of 2.1 K and radiative forcing of 3.5 Wm^{-2} per doubling of CO_2 (27). The extra radiative forcing in the Global case due to the excess 381 ppmv of CO_2 at year 2100 would produce an equilibrium carbon-cycle warming of $\approx$1.3 K. If we further assume that the transient temperature difference of 0.3 K between the Global case and Standard experiment (Fig. 1*A*) remains the same at equilibrium, the cooling from net biophysical effects is $\approx$1.6 K.

Caution should be exercised in interpretation because the results are from a single modeling study. The INCCA terrestrial biosphere component model IBIS2 has higher carbon uptake with increased atmospheric CO_2 than similar models (32). This model anomaly would tend to accentuate the simulated difference between the atmospheric CO_2 in our deforestation simulations relative to our Standard simulation, thereby overestimating the warming carbon-cycle effects of global-scale deforestation relative to its biophysical cooling effects. With a less-responsive biosphere model, we would expect to see even more cooling as a result of deforestation. The magnitude of the model-predicted net cooling from large-scale deforestation thus may be smaller than what would actually be seen. Multimodeling

Table 1. Climate variable differences between Global and Standard experiments for the decade centered on year 2100

	Global	Global land	SH mid-latitude land (50°S to 20°S)	Tropical land (20°S to 20°N)	NH mid-latitude land (20°S to 50°N)	NH high-latitude land (50°S to 90°N)
Surface temperature, K	−0.3	−1.0	0.1	−0.4	−1.6	−2.1
Evapotranspiration, %	−2.6	−7.8	−16.7	−5.8	−5.8	−14.6
Surface albedo, %	1.9	5.2	5.0	4.1	4.7	10.7
TOA albedo, %	0.6	1.6	0.5	−0.3	1.7	5.5
Total cloudiness, %	−0.7	−1.7	−4.7	−4.6	−1.2	2.5
Surface SW absorbed, Wm^{-2}	−1.4	−4.3	−1.7	1.2	−5.2	−13.8
Surface downward SW, Wm^{-2}	2.2	5.1	11.3	12.9	3.0	−3.2

Evapotranspiration percentage differences are relative to Standard mean climate for this period. Cloudiness and albedo changes are absolute changes. SH, Southern Hemisphere; NH, Northern Hemisphere; TOA, Top of Atmosphere; SW, shortwave.

and model intercomparison studies are needed to confirm and better quantify our results.

Many of our conclusions are consistent with inferences drawn from previous studies that focused solely on radiative forcing (7) or used simpler climate models (20–22): the climate effects of CO_2 storage in forests are offset by albedo changes at high latitudes, so that from a climate change mitigation perspective, projects promoting large-scale afforestation projects are likely to be counterproductive in these regions.

We find that tropical deforestation contributes to global warming from net carbon-cycle and biophysical effects (Fig. 3*E*), supporting conclusions drawn in earlier studies (20). The tropical cooling seen in the Global deforestation experiment (Table 1) therefore implies the presence of remote effects of deforestation implemented elsewhere (28–31). Nonetheless, this net tropical temperature change is small, and so its sign may be sensitive to the representation of physical processes such as cloud dynamics and surface hydrology in the model (33).

The results presented here highlight the need to employ climate-carbon models to comprehensively evaluate the carbon-cycle and biophysical effects of forests on climate. For example, although the importance of time horizon in defining tradeoffs between carbon and biophysical effects is evident (e.g., increasing ocean uptake in Fig. 2), this aspect of the problem has been largely overlooked in previous assessments. Another policy-relevant implication is that large-scale afforestation implemented in temperate latitudes may be largely ineffectual in mitigating global warming. We note, however, that results for

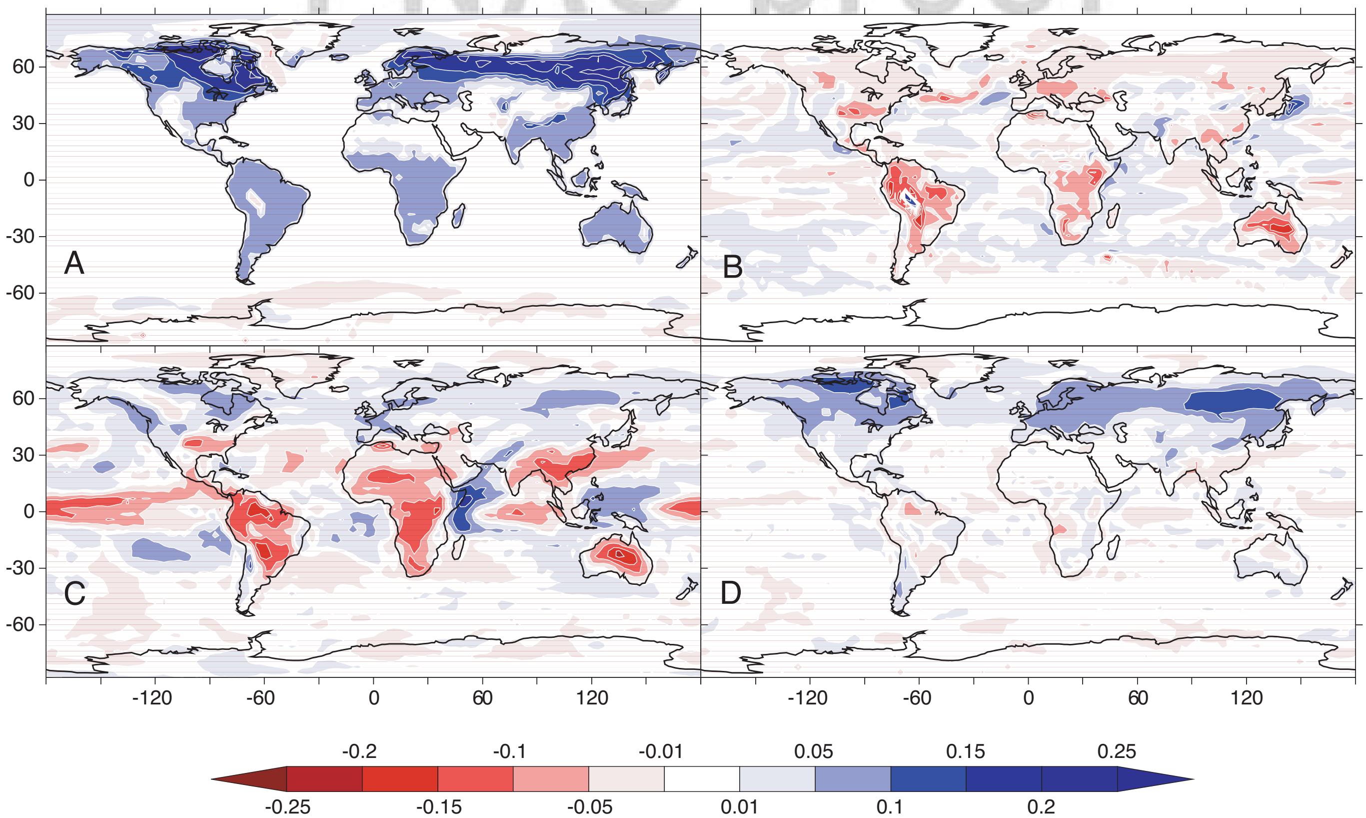

Fig. 4. Simulated spatial pattern differences (Global minus Standard) in the decade centered on year 2100 for the surface albedo (fraction) (*A*), evapotranspiration rates (cm/day) (*B*), cloudiness (fraction) (*C*), and planetary albedo (fraction) (*D*) differences. Albedo effects dominate the Northern Hemisphere mid- and high-latitude climate change and produce a strong cooling in Global relative to Standard. In the tropics and Southern Hemisphere land areas, the warming due to higher atmospheric CO_2 is largely offset by cooling biophysical effects, producing little net temperature change. In the tropics, removal of forests increases surface albedo (*A*) and decreases evapotranspiration (*B*). The reduction in evapotranspiration decreases cloudiness (*C*), which reduces albedo as seen from the top of the atmosphere (*D*), largely offsetting the effects of the increased surface albedo.

Table 2. Surface temperature changes (K), relative to Standard, in Global, Tropical, Temperate, and Boreal deforestation experiments

Deforestation experiments	Global-mean	Global land mean	SH mid-latitude land (50°S to 20°S)	Tropical land (20°S to 20°N)	NH mid-latitude land (20°S to 50°N)	NH high-latitude land (50°S to 90°N)
Global	−0.3	−1.0	0.1	−0.4	−1.6	−2.1
Tropical	0.7	0.9	0.8	0.2	1.1	1.7
Temperate	−0.04	−0.2	−0.3	0.07	−0.7	0.4
Boreal	−0.8	−1.4	−0.3	−0.3	−1.6	−3.8

SH, Southern Hemisphere; NH, Northern Hemisphere.

specific forest species in particular locations could vary from the global-scale results presented here. Furthermore, because carbon-cycle effects are manifested globally whereas biophysical effects are most strongly felt locally, a particular afforestation project could produce regional warming while cooling the remainder of the planet.

Finally, we must bear in mind that preservation of ecosystems is a primary goal of preventing global warming, and the destruction of ecosystems to prevent global warming would be a counterproductive and perverse strategy. Therefore, the cooling that could potentially arise from deforestation outside the tropics should not necessarily be viewed as a strategy for mitigating climate change because, apart from their potential climatic role, forests are valuable in many aspects. They provide natural habitat to plants and animals, preserve the biodiversity of natural ecosystems, produce economically valuable timber and firewood, protect watersheds through prevention of soil erosion, and indirectly prevent ocean acidification by reducing atmospheric CO_2. In planning responses to global challenges, therefore, it is important to pursue broad goals and to avoid narrow criteria that may lead to environmentally harmful consequences.

Model Experiments

In this study, we discuss six INCCA model simulations starting from the year 2000. In a "Standard" experiment without deforestation effects, CO_2 emissions follow historical levels for the period 1870–2000, SRES A2 levels (34) for the period 2000–2100, and a logistic function (23) for 2100–2150. This Standard simulation, which has been extensively discussed in our previous INCCA modeling studies (23–25), produces a global-mean warming in year 2100 that is 3.2 K greater than that of a "Control" simulation in which there are no CO_2 emissions and other greenhouse gases are fixed at preindustrial levels. Four other experiments with different configurations of large-scale deforestation also are simulated. A "Global" experiment that brackets the climatic effects of global-scale deforestation is identical to the Standard experiment except that plant functional types representing trees are not allowed to exist after year 2000, and thus only shrub and grass plant functional types remain. The biomass in tree leaves and fine roots is immediately transferred to the litter pool in year 2000, and the stem biomass becomes litter on a time scale of ≈10–50 years depending on the tree plant functional type. In this simulation, the total carbon released to the atmosphere from tree functional types in the 21st century is 818 PgC.

To isolate the net effects of large-scale deforestation implemented in tropical, temperate, and Northern high latitudes, we consider three additional simulations where deforestation is restricted to the latitude bands 20°S to 20°N ("Tropical"), 20–50° in both the Northern and Southern Hemispheres ("Temperate"), and 50–90° in the Northern Hemisphere ("Boreal"), respectively. The corresponding amounts of carbon released from trees in these latitude bands in the 21st century are 422, 316, and 80 PgC, respectively. Note that the sum of carbon lost from tree plant functional types in these three latitude band simulations is equivalent to the tree carbon lost in the Global case.

We recognize the ecological complexities associated with our deforestation scenarios. Maintaining grasslands in regions that previously supported forests would require a substantial change in the disturbance regime. Either fire or intensive grazing or agriculture would be required to keep forests from growing back, at least initially, and all of these forms of disturbance would have large consequences for other radiative forcing agents including methane, aerosols, nitrous oxide, and ozone. Treatment of all of these biogeochemical processes is currently outside the scope of contemporary modeling capabilities.

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