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Climatic Consequences of Afforestation

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Abstract. One strategy proposed to mitigate the climate change associated with increased greenhouse gases is to plant more trees, which absorb carbon dioxide in the process of photosynthesis. We have used a climate model to explore the possible impact of a large-scale afforestation, both in the Arctic and at mid-latitudes in the northern hemisphere. The global climate responds in surprising ways, largely because of the water vapor released by plant transpiration. The experiments illustrate the importance of exploring the entire spectrum of consequences from any proposed action to deal with climate change.

INTRODUCTION

Global climate models are the principal tool for projecting global and regional climate change in response to different anthropogenic activities. They solve the equations for the conservation of mass, angular momentum, and energy for the atmosphere and the oceans. The models include also prognostic equations for the distribution of water vapor in the atmosphere and of salinity in the oceans. Typically the time histories of atmospheric composition and land cover are specified, and the model is integrated forward in time, to yield the transient or equilibrium climate response. A new generation of climate models predicts, rather than specifies, the abundance of CO_2 and other trace constituents in the atmosphere. For CO_2, the trajectory of fossil-fuel emissions is specified, and the atmospheric CO_2 increment is the residual after climate-sensitive interactions with the land biosphere and the oceans are taken into effect. [1, 2]

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ESTIMATES OF CLIMATE FORCING

The main driver of climate change is the radiative forcing (in watts per square meter, W/m^2) contributed by various agents external to the climate system. The forcing associated with each greenhouse gas is determined by the change in the abundance of the gases since the pre-industrial era together with its absorption spectrum. Figure 1 summarizes the changes in forcings that the Fourth Assessment Report of the Intergovernmental Panel on Climate Change found to be associated with the changes in atmospheric composition since the preindustrial era [3]. Note that the radiative forcing for greenhouse gases is not in proportion to their abundance in the atmosphere, as the molecules with more vibrational and rotational degrees of freedom are more potent absorbers. Thus, the forcing associated with each additional molecule of chlorofluorocarbon (CFC) is about 10,000 times greater than that associated with a molecule of CO_2, and the radiative forcing by CFC is 20-25% that of CO_2, even though the abundance of CFC is several orders of magnitude smaller than that of CO_2.

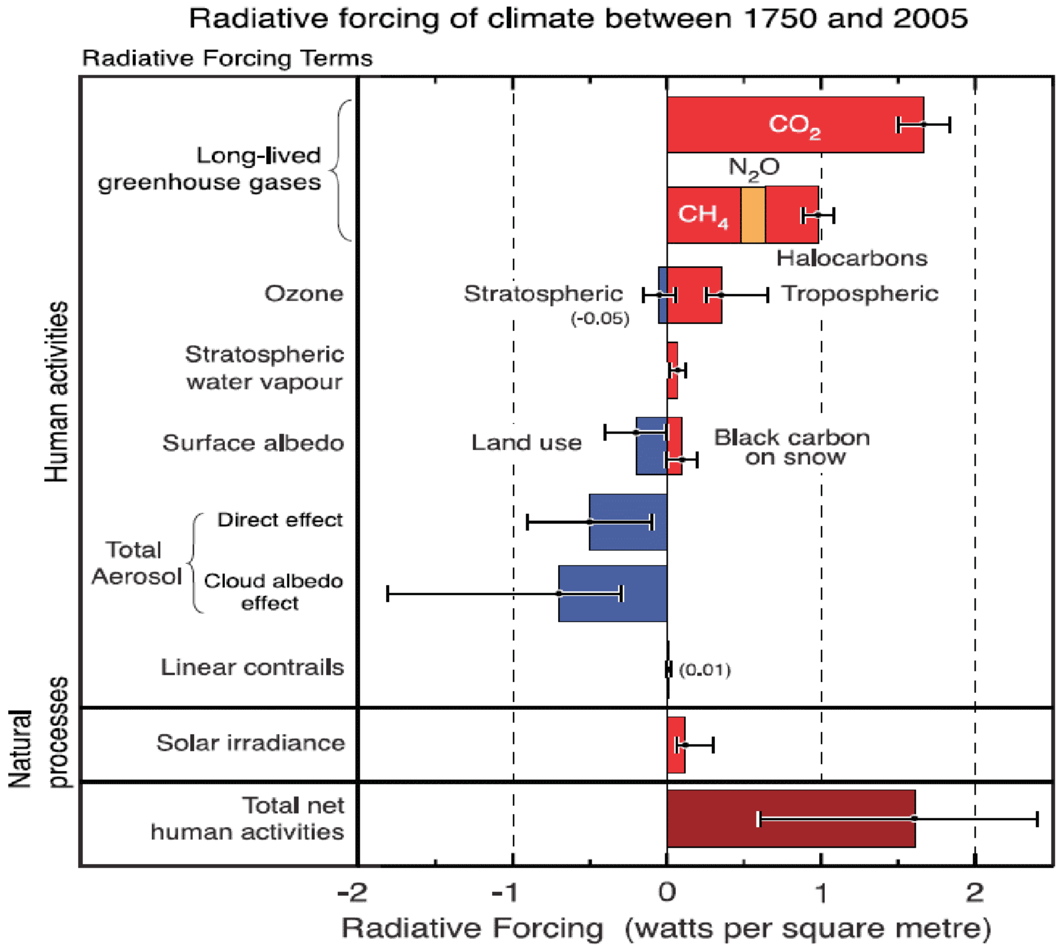

FIGURE 1. Changes in Radiative Forcing. Estimates done by the Intergovernmental Panel on Climate Changes for its 2007 report.[1] The table lists the changes in forcings (in watts per square meter) calculated for various changes in atmospheric constituents caused by man's activities since the preindustrial age.

Figure 1 also includes both the direct and indirect forcing associated with aerosols. While most aerosols reflect sunlight, some (e.g. mineral aerosols, soot) can also absorb in the visible and/or the infrared parts of the spectrum. Hence, the direct forcing can be either positive or negative, but the net impact of the increase in aerosols is estimated to be a negative forcing. The magnitude of the forcing depends on the size of the aerosols as well as their concentrations. For the same aerosol mass, the number density and hence total reflective area are inversely proportional to aerosol radius, and so small droplets are more reflective than large ones. The indirect effect of aerosols results from their ability to act as cloud condensation nuclei and influence cloud microphysics and cloud dynamics. There is large uncertainty associated with the cloud effect, as reflected in the large error bars shown.

The net sum of all the global mean forcings from 1750 to 2005, as summarized in Figure 1, is a radiative forcing of 2.9 +/- 0.3 W/m^2 from greenhouse gases, countered by the negative forcing from aerosols, with a median of -1.3 W/m^2 and a range of -2.2 to -0.5 W/m^2 90% confidence range. The combined forcing is thus 1.6 W/m^2 with a 0.6 to 2.4 W/m^2 90% confidence range. Greenhouse gases are typically long-lived, with lifetimes of weeks to centuries and longer, while aerosols have much shorter lifetimes, typically days to weeks. Hence climate change would be greater without the effects of mostly polluting aerosols.

CLIMATE FEEDBACKS

The radiative forcing can be amplified or diminished by feedbacks internal to the climate system. The major feedbacks are associated with the three phases of water are summarized in Figure 2. As the climate warms, increased evaporation from the oceans leads to an increase in atmospheric water vapor, itself a greenhouse gas, thus leading to more heating that magnifies the initial warming, i.e. a positive feedback. The vapor exceeding the saturation threshold condenses and forms clouds which reflect sunlight, leading to a reduction in the warming, i.e. a negative feedback. Finally, warming causes the melting of the snowpack and sea ice, leading to a decrease of surface albedo, enhanced solar absorption and greater warming -- a positive feedback.

Although the net feedback associated with cloud changes is expected to be negative, the uncertainties are large. The impact of a cloud on climate depends greatly on its horizontal and vertical extent, among other things, and hence its impact on both the solar and infrared radiation. Contrast, for example, tall cumulonimbus clouds in the tropics with maritime stratus clouds off the coast of California. Cumulonimbus towers are narrow, with tops at high altitudes. Because temperature decreases with height, high clouds radiate at a colder temperature than low clouds, and so could have a net warming effect because of the reduced energy loss to space. Maritime stratus clouds, which are low and have a large areal coverage, reflect more sunlight and have a cooling effect on climate. This is an active area of research.

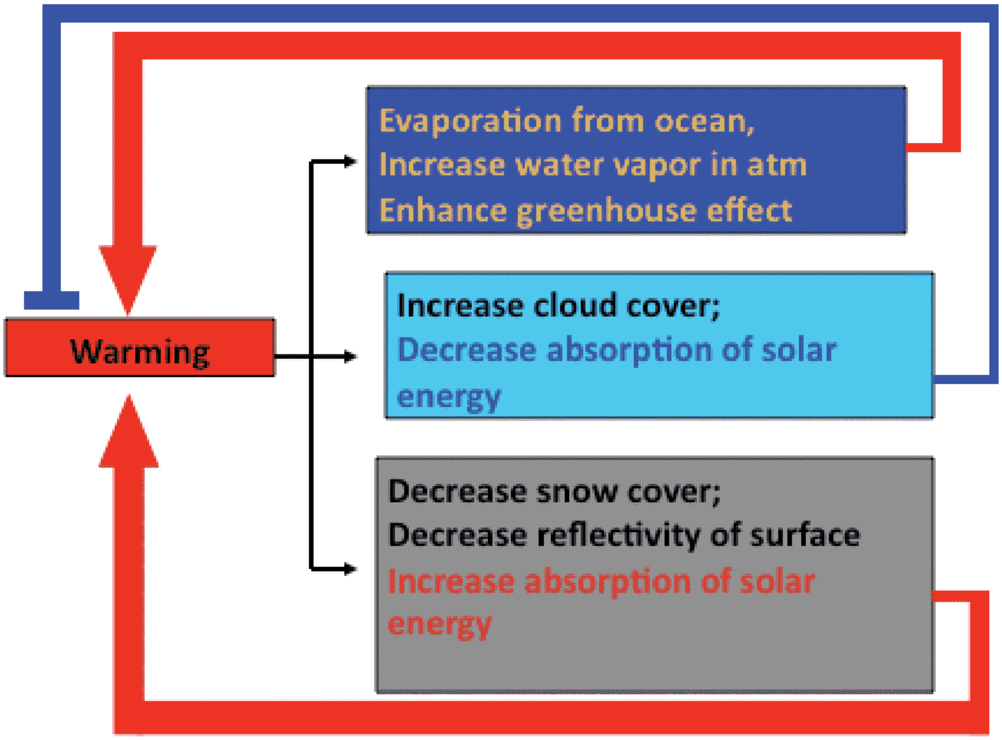

FIGURE 2. Climate Feedbacks associated with changes in the phase of water.

AFFORESTATION AND CLIMATE CHANGE

Large-scale planting of trees has been proposed as a climate-mitigation strategy, as carbon is removed from the atmosphere via photosynthesis and stored in the forests. Such large-scale modification of the land surface also impacts the climate directly. Vegetation influences the surface energy budget in several ways. First, albedo is determined by the type of landcover. Trees growing in a previously snow-covered area would lead to a decrease in albedo, with the decrease much less for the brighter deciduous trees than for the darker evergreen trees. A second impact on the energy balance is the change in net longwave radiation, which is determined by the vertical profiles of temperature and greenhouse gases (especially water vapor) in the atmospheric column. The net radiation (net solar minus net longwave radiation) is countered by latent and sensible heat fluxes, with the residual energy heating the surface. Latent heat flux is dominated by transpiration from plants and evaporation from the soil, both of which contribute water vapor to the atmosphere. Deciduous trees transpire more than evergreen trees. Sensible heating directly warms the air above the surface.

We carried out two sets of afforestation experiments with the carbon-climate model of the National Center for Atmospheric Research [4] to explore the impact of afforestation on climate. We were interested in the resultant equilibrium climate, and so the atmospheric general circulation model was coupled to a simplified ocean. Each set of experiments comprises four model runs, two with the oceans represented by a simple "slab" ocean, with interactive thermodynamics but prescribed heat transports, and two with prescribed sea surface temperature and sea ice conditions, so that the oceans do not play a role in the resultant climate change. For each ocean configuration, the vegetation is either left as is (the "control run") or modified (described below). Each run was integrated to equilibrium.

In the first set of experiments, we replaced bare ground in the Arctic with deciduous trees in the model[5]. The experiment is motivated by suggestions that broad-leaf trees may invade warming tundra more readily than evergreen trees would [6]. Furthermore, evidence for such vegetation has been seen in paleoclimate data for warm periods in the past.[7]

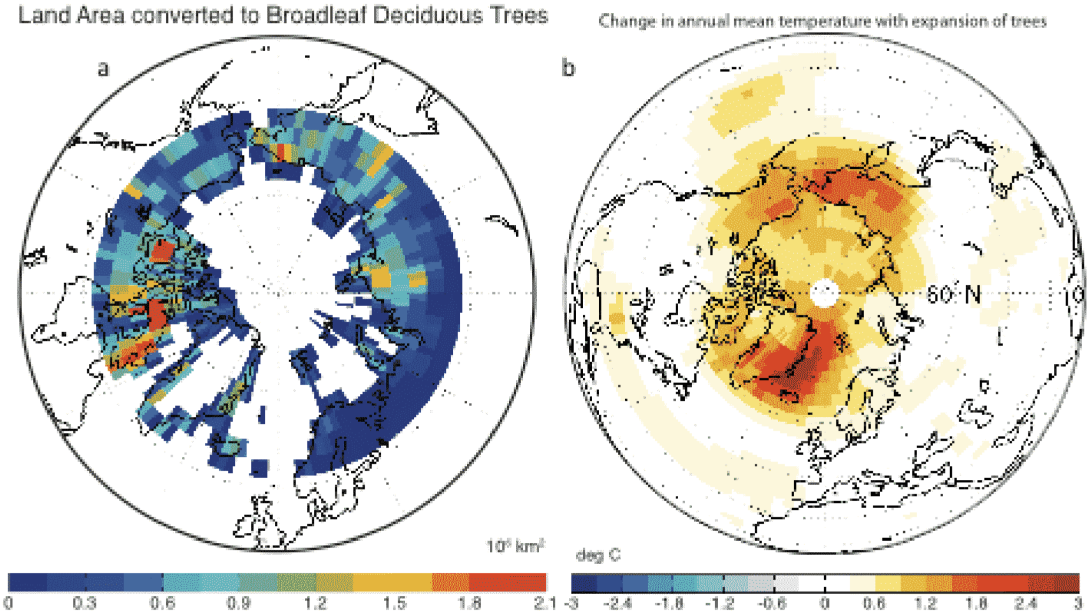

FIGURE 3. Arctic Afforestation Experiment. (a) Bare ground area converted to deciduous forests in the climate model. (b) Near-Surface temperature anomalies (Kelvin). From Swann *et al.* (2010).

The results of our study are illustrated in Figure 3. In the model runs with interactive oceans, we found, to our surprise, widespread temperature increases across the Arctic, exceeding 2°C in places, even away from the afforested areas. In particular, we found that the top-of-atmosphere radiative imbalance from enhanced transpiration (associated with the expanded forest cover) is up to 1.5 times larger than the forcing due to albedo change from the forest. Furthermore, the greenhouse warming by the additional water vapor transpired melts sea-ice and triggers a positive feedback through changes in ocean albedo and evaporation. Land surface albedo change has been considered to be the dominant mechanism by which trees directly modify climate at high-latitudes, but our experiments suggest an additional mechanism through transpiration of water vapor and feedbacks from the ocean and sea ice. The amplification of the warming is not found in the runs with prescribed ocean.

To understand these results, we employed a 1-D (vertical) radiative-convective model, in which the impacts of a single perturbation can be assessed, with all other variables held at the values of the control run. We estimated the changes in the forcing at the top of the atmosphere caused only by a change in albedo and only by an increase in water vapor due to transpiration in the runs with fixed ocean conditions. The two forcings are comparable, ~1 W/m^2 averaged poleward of 60°N. Because water vapor is rapidly mixed in the Arctic atmosphere, the increased water vapor greenhouse effect over the Arctic ocean in the run with an interactive ocean leads to an enhanced ice-albedo feedback, associated with melting sea ice, increased evaporation from the open ocean.

MID–LATITUDE AFFORESTATION

In our second set of experiments, we replaced mid-latitude grasslands and croplands with deciduous forests.[8] Again, in the model runs with an interactive ocean, we found widespread warming, extending well beyond the afforested areas (Figure 4). To start, the northern hemisphere surface is darkened, leading to increased absorption of solar radiation. The subsequent changes are however quite different from those in the Arctic: transpiration is limited by the finite amount of moisture in the soils, and the mid-latitude atmosphere has a greater moisture capacity than the cold Arctic atmosphere. Thus enhanced transpiration contributes only a relatively small increase in water vapor in the mid-latitudes and the water vapor greenhouse effect, while positive, is weak. Ice-albedo feedback is also weak, due to distance from the forcing. The change in net radiation is no longer balanced by changes in latent heat loss, but by changes in sensible heat loss from the surface, which directly warms the atmosphere.

An unexpected consequence of the warmer northern hemisphere is a shift in the position of the intertropical convergence zone (ITCZ), the rain belt that demarcates the Northern and Southern Hadley cells (Figure 5). The Southern Hemisphere Hadley cell expands northwards to enhance heat transport from the warmer to the cooler hemisphere: a northward shift in the rain belt results. Such changes in global circulation lead to changes in net primary production worldwide: net primary production decreases in the southern Amazon, because of the drying (Figure 6).

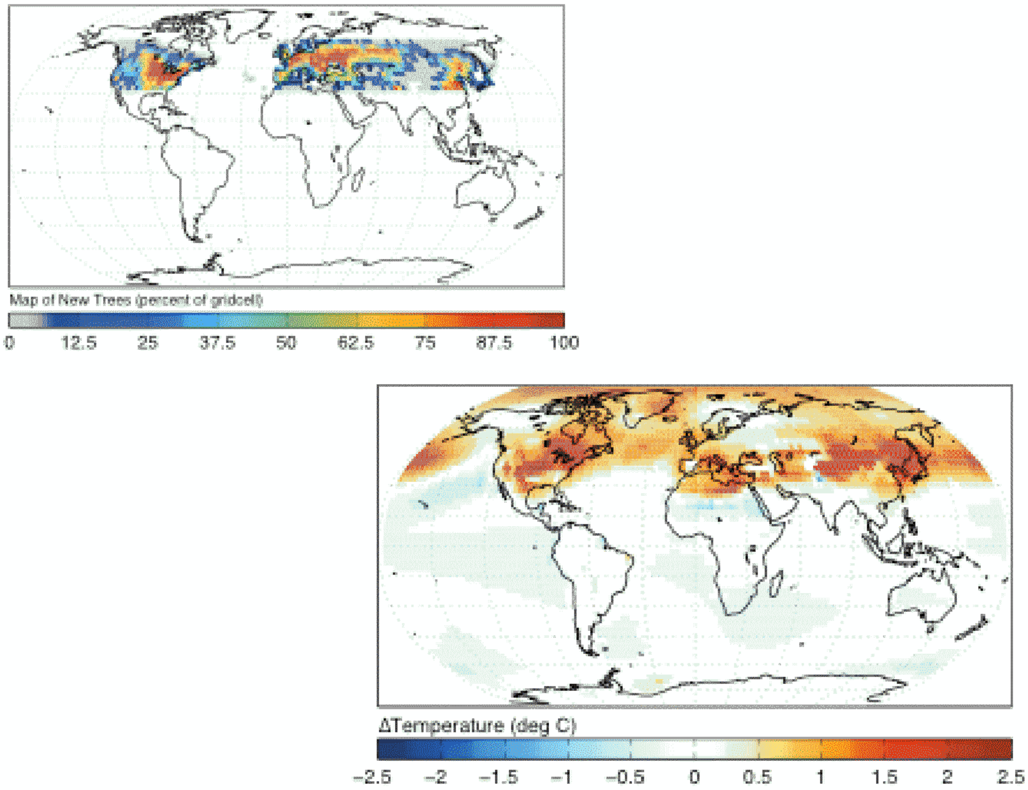

FIGURE 4. Mid-Latitude Afforestation Experiment. (a) Areas in which deciduous trees were assumed to replace grassland or cropland in the climate model. (b) The resulting temperature changes. Note that temperatures were affected even well beyond the afforested regions. From Swann et al. (2011).

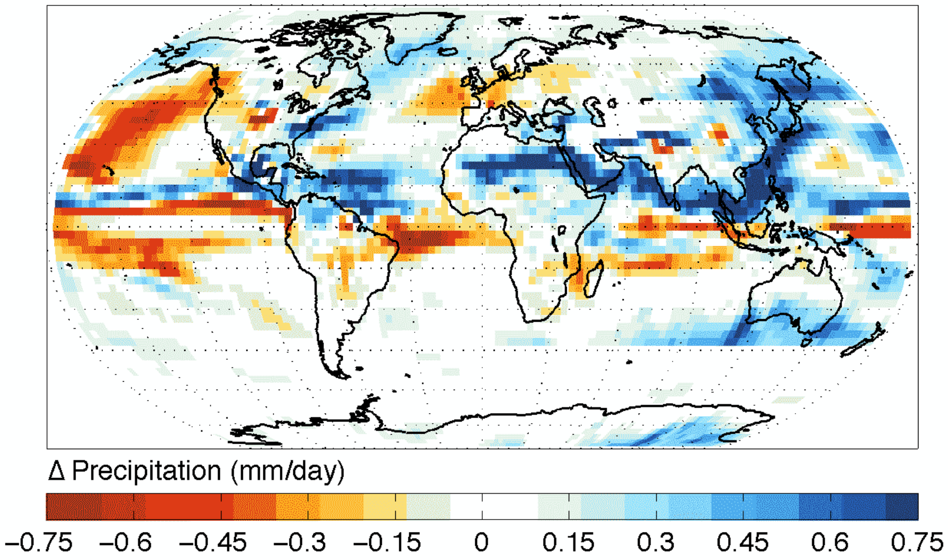

FIGURE 5. Teleconnections. The northern hemisphere warming caused by the hypothetical planting of mid-latitude trees led to changes in atmospheric circulation and changes in precipitation patterns. From Swann *et al.* (2011)

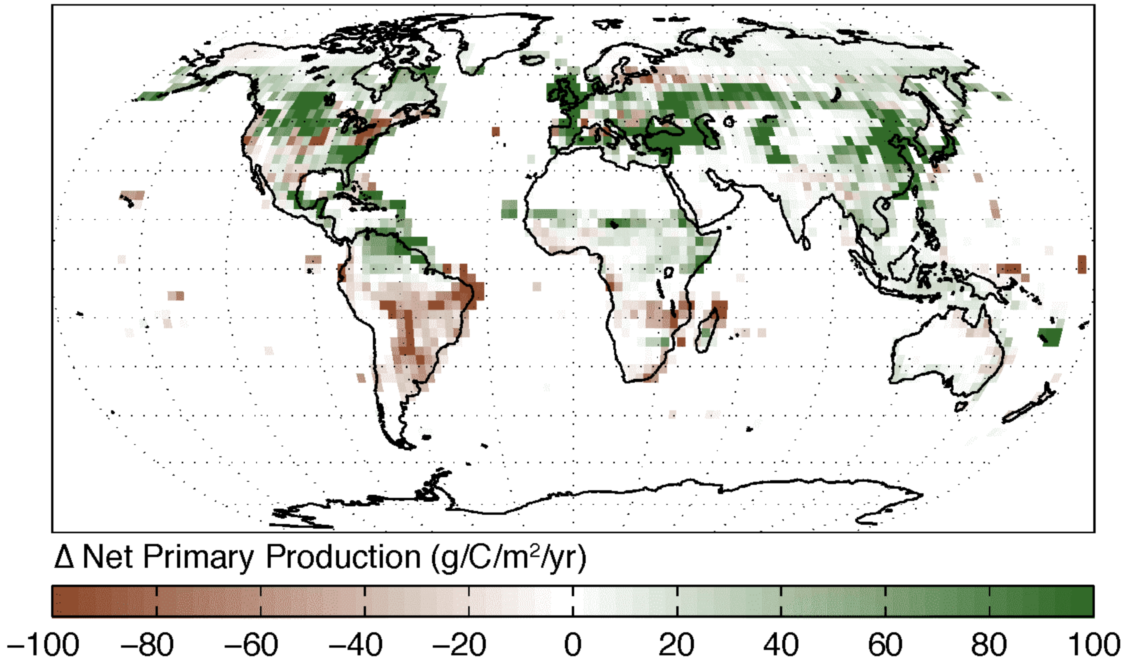

FIGURE 6. Changes in Net Primary Productivity (NPP). The changed precipitation patterns caused by the warming of the northern hemisphere had implications for the growth of vegetation throughout the world. From Swann *et al.* (2011).

CONCLUDING REMARKS

The afforestation experiments with the climate model prescribed landcover changes on a scale much larger than any afforestation project under consideration. Still, the results serve to underscore the kinds of unexpected consequences that might ensue and hence inform climate modification strategies. Our mid-latitude afforestation experiment resulted in an additional storage of 230 petagrams carbon (1 Pg = 10^{15} g) carbon in the terrestrial biosphere. The removal of this much carbon from the atmosphere would produce a global cooling of 1–2.2 °C. However, a decrease in the atmospheric carbon alters the gradient in CO_2 partial pressure across the air-sea interface and leads to an outgassing of carbon from the oceans. The resultant net drop in atmospheric carbon is only 30–50 Pg C, and the global cooling is small while the latitudinal gradient in temperature, which is the driving force for changes in circulation, remains (Swann et al. 2011). Such a global perspective obscures substantial regional changes in ocean, atmosphere and ecosystems.

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