

Green surprise? How terrestrial ecosystems could affect earth's climate

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While the earth's climate can affect the structure and functioning of terrestrial ecosystems, the process also works in reverse. As a result, changes in terrestrial ecosystems may influence climate through both biophysical and biogeochemical processes. This two-way link between the physical climate system and the biosphere is under increasing scrutiny. We review recent developments in the analysis of this interaction, focusing in particular on how alterations in the structure and functioning of terrestrial ecosystems, through either human land-use practices or global climate change, may affect the future of the earth's climate.

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Climatic conditions, including rainfall, seasonal water balance, the length of growing seasons, and winter temperatures, can strongly influence plant and animal species (Prentice *et al.* 1992; Woodward *et al.* 1995). Changes in climate may therefore have a profound impact on terrestrial ecosystems worldwide. Many studies have shown how climatic variations in the recent geologic past have caused major shifts in the composition and distribution of terrestrial ecosystems (eg COHMAP 1988). The possibility of future climate change, fueled by increases in greenhouse gases, has also spurred speculation on the future makeup of the biosphere (Cramer *et al.* 2001).

While it may be obvious that the climate affects terrestrial ecosystems, terrestrial ecosystems can also affect the climate, particularly through their vegetative cover and soils. This may happen by means of processes that are both biophysical (ie changes in water, energy, or momentum balance) and biogeochemical, including changes in the proportion of important trace gases, such as CO₂ and methane, in the atmosphere.

We have become increasingly aware of this two-way link. A new generation of computer models has been developed over the past decade to analyze this coupled

behavior (eg Foley *et al.* 1998, 2000; Cox *et al.* 2000; Delire *et al.* in press). These models are useful for examining how variations in the structure and functioning of terrestrial ecosystems can affect the evolution of the climate system, either through human land-use practices or the impacts of global climate change.

■ Biophysical impacts of changing land use and cover

The atmosphere responds to the exchange of energy, water, and momentum from the land, ocean, or ice. Any change in this surface flux can strongly affect atmospheric thermodynamics and circulation – changes such as an increase in ocean temperatures during an El Niño event, the collapse of a massive ice sheet, or the replacement of a tropical rainforest with pasture.

Changes in land use and cover can also affect biophysical surface fluxes in several ways. First, they can modify the surface albedo (the fraction of solar radiation that is reflected), thereby changing the energy balance and the surface temperature. This, in turn, affects how the surface cools itself, by shifting the balance between sensible heat loss (the cooling of a warm surface by the wind) and latent heat loss (cooling through evapotranspiration). Finally, vegetative height and density affect the roughness of the land surface, which itself influences the mixing of air close to the ground. Rough surfaces mix air more efficiently, enhancing both cooling processes. Changes in albedo, surface roughness, and the ratio between sensible and latent heat loss can all affect surface fluxes and, as a result, modify the climate.

Much of the world's land surface has already been cleared for agriculture or human settlements. Together, croplands, pasture, and urban areas cover nearly 35% (about 55 million km²) of the continental surfaces (Ramankutty and Foley 1999; Ramankutty *et al.* unpublished). To a large extent, the only two remaining areas to be exploited for human use, excluding the desert and polar regions, are the tropical rainforests of South America, Africa, and Southeast Asia, and the boreal forests of

In a nutshell:

- Traditionally, discussions of climatic change have focused on how such changes will affect ecosystems
- Recent work suggests that changes in ecosystems can, in turn, affect climate
- Preliminary computer modeling studies indicate that ecosystems may produce “positive feedbacks” on global warming, making the planet warmer than originally expected
- Further research is needed to quantify the role of ecological feedbacks in the climate system

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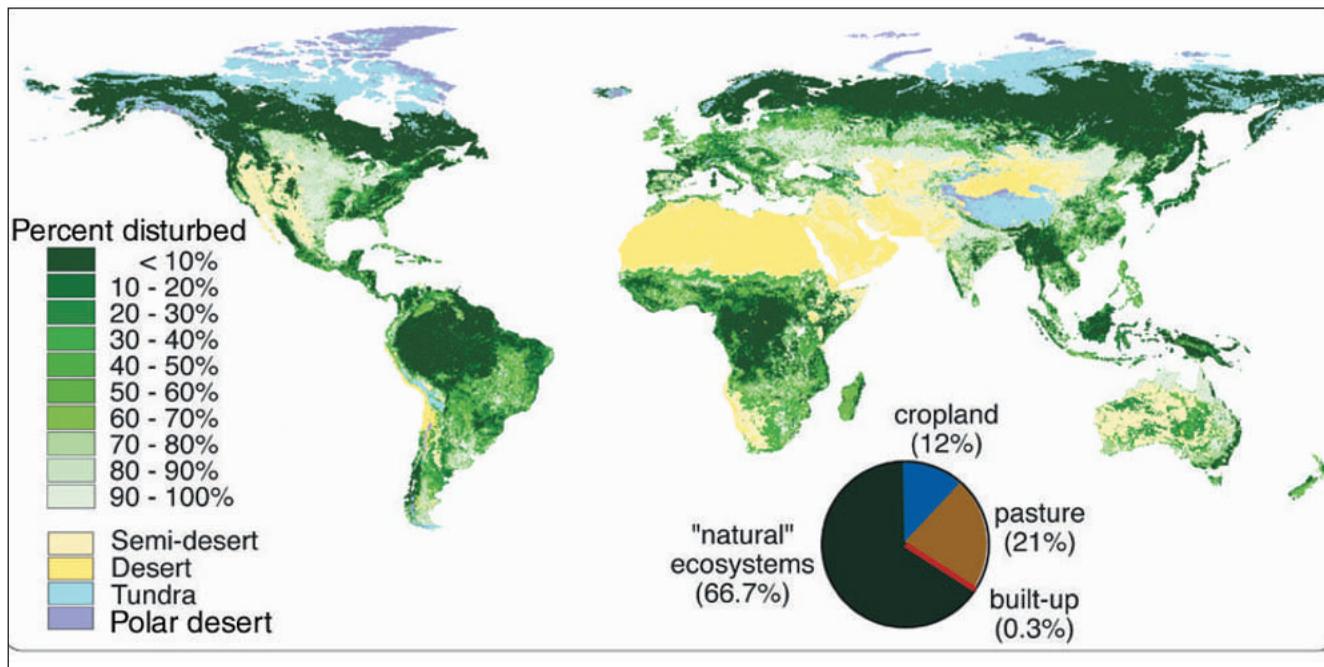


Figure 1. The global extent of human land use, including croplands, pastures, and urban settlements across the world. Data from Ramankutty and Foley (1999) and Ramankutty *et al.* (unpublished).

Canada and Russia (Figure 1). Pressures to develop these last frontiers are increasing, especially as growing human populations continue to demand more and more forest and agricultural products.

The effects of tropical deforestation on climate have been analyzed many times in the past two decades (Dickinson and Henderson-Sellers 1988; Lean and Warrilow 1989; Costa and Foley 2000). Typically, the climatic impacts of tropical deforestation have been evaluated using a global climate model (GCM), linked to a biophysical land surface model that explicitly represents the characteristics of changing vegetation cover (eg changes in canopy height, leaf density, or rooting depth).

According to most climate modeling studies, large-scale patterns of tropical deforestation will probably cause a considerable increase in surface temperature and a decrease in annual rainfall and evapotranspiration (Bonan 2002; Costa *in press*). These changes result from fundamental shifts in the surface energy, water, and momentum balance that accompany deforestation (Figure 2). In general, replacing a tropical forest with a grassland or pasture increases albedo and decreases roughness, green leaf area index, and vegetation rooting depth (Costa and Foley 2000).

Changes in temperature as a result of tropical deforestation can affect both surface energy and water budgets. First, the increase in albedo tends to cool the surface, by reducing the amount of solar radiation it can absorb. However, surface roughness, leaf area, and root depth are lower in pastures than in forests; this dramatically reduces evapotranspiration from the smoother surface, which in turn substantially increases its temperature. As a result, the cooling effect of the higher albedo is completely offset, and often surpassed, by the reduction in evaporative cool-

ing. The net effect is a warming of approximately 1–2 °C in tropical regions undergoing large-scale deforestation (Costa and Foley 2000).

The reduction in precipitation in these huge cleared areas is also a consequence of the changes in the energy and water balance. First, the reduction in absorbed solar radiation and the increase in surface temperature both lead to a decrease in the net radiative heating of the land surface, defined as the difference between absorbed solar radiation and outgoing longwave (infrared) radiation. This leaves less energy to fuel atmospheric circulation, which ultimately results in a cooling of the upper atmosphere, followed by subsidence (sinking air) and less precipitation over the deforested region (Eltahir 1996). Second, the reduction in surface roughness, leaf area, and root depth dramatically limits how much water vapor can be recycled into the atmosphere locally through evapotranspiration – an important component of the hydrologic cycle of tropical rainforests (Salati *et al.* 1979; Eltahir and Bras 1994; Costa and Foley 1999). By reducing evapotranspiration, deforestation results in less water being pumped into the atmosphere, thereby contributing to the decrease in rainfall.

The effects of deforestation on the tropical climate may enhance the impacts of global warming. Costa and Foley (2000) suggested that the increases in temperature associated with deforestation in the Amazon basin may be around 1.4 °C, compared to a warming of approximately 2.0 °C that would be expected from a doubling of atmospheric CO₂. They also showed that tropical deforestation would lead to a substantial decrease in rainfall over the Amazon basin, while global warming might increase rainfall. The net effect of global warming and widespread

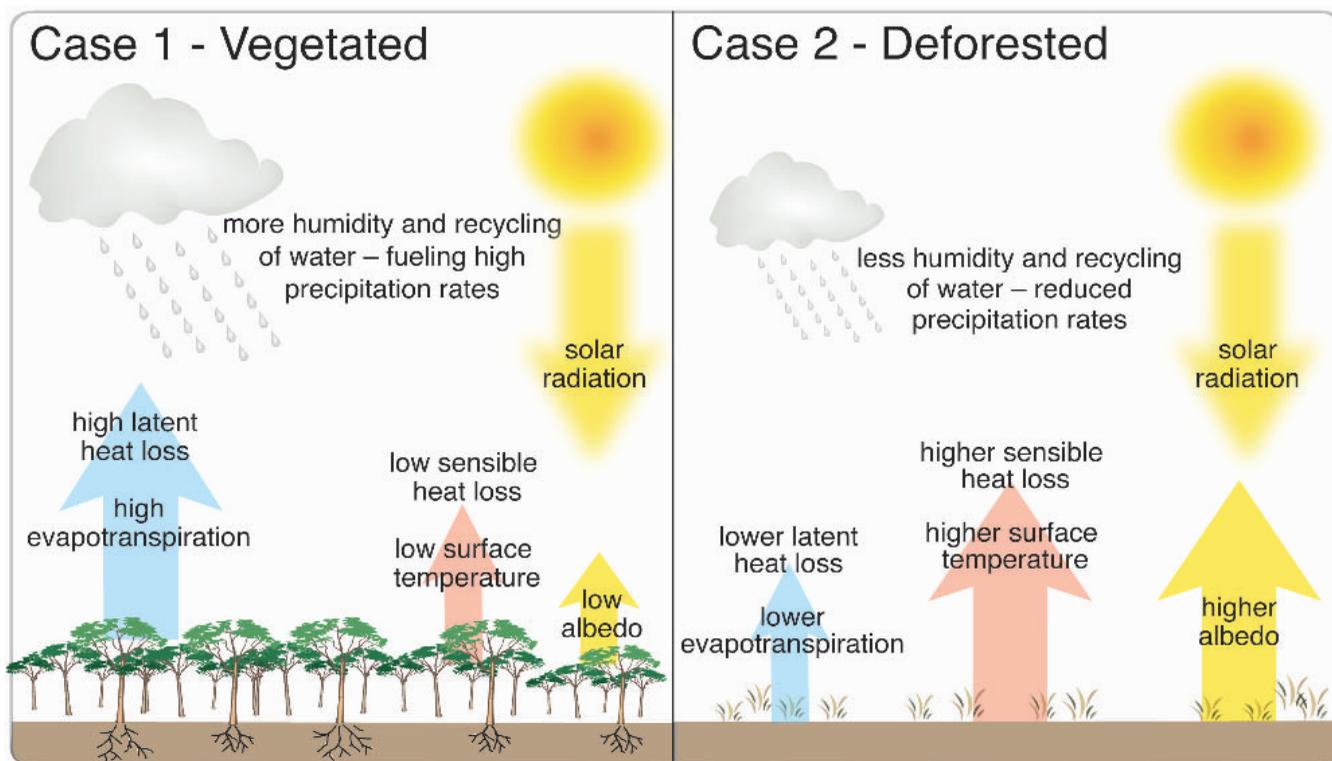


Figure 2. Climatic effects of tropical deforestation on water balance, boundary layer fluxes, and climate. In vegetation-covered areas (left), the low albedo of the forest canopy provides ample energy for the plants to photosynthesize and transpire, leading to a high latent heat loss that cools the surface. In deforested areas (right), bare soil's higher albedo reduces the amount of energy absorbed at the surface. Latent heat loss is severely reduced and the surface warms, as it has no means of removing the excess energy through transpiration.

deforestation in the Amazon may therefore be a significantly warmer and somewhat drier local climate.

While the impacts of tropical deforestation have received considerable attention, other studies have shown that land-use and land-cover change in semi-arid (Zeng *et al.* 1999; Wang and Eltahir 2000a, 2000b, 2000c, 2000d), temperate (Copeland *et al.* 1996; Bonan *et al.* 1997, 1999; Reale and Dirmeyer 2000; Reale and Shukla 2000; Heck *et al.* 2001) and boreal ecosystems (Bonan *et al.* 1992, 1995) can also greatly affect the climate.

In addition, several modeling exercises have examined the consequences of global-scale land-cover changes on climate systems (eg Betts 1999; Bounoua *et al.* 2002; Brovkin *et al.* 1999; Zhao *et al.* 2001). These studies have shown that such changes can substantially affect the climate over large regions – sometimes more than the changes expected from global warming. These effects are mainly confined to a few geographic regions, however.

Characterizing the climatic significance of land-cover change is not as easy as discussing global warming. There are no simple generalities; some regions become warmer while others become colder, some become wetter as others become drier. As a result, the impacts on the global climate are fairly small on average. Unlike the warming effect of increasing greenhouse gases, these variations are extremely dependent on geography, and cannot simply be reduced to an average value. Any assessments of future cli-

mate change should therefore consider both the impacts of greenhouse gases and land-use practices on local, regional, and global scales.

■ Biophysical feedbacks on global warming

What about indirect effects on vegetation cover that might result from global warming? Could shifting plant patterns also affect the climate, and would these changes amplify or reduce the warming effects?

Biophysical feedbacks can occur through the two-way interactions between climate and vegetation cover (Figure 3). For example, global warming may affect the structure and distribution of terrestrial ecosystems around the world. These climate-induced changes may affect biophysical processes at the land–atmosphere boundary and, as a result, create a positive or negative feedback effect.

A new suite of computer models has recently been developed to consider the interactions between vegetation and climate. Most of these models are based on existing GCMs of the atmosphere, linked to representations of land surface processes and global vegetation dynamics (Foley *et al.* 1998, 2000). These models build on a long tradition of global climate modeling and the more recent inclusions of detailed, mechanistic models of surface biophysical processes. Coupled climate–vegetation models are still in the early development stages, however, and

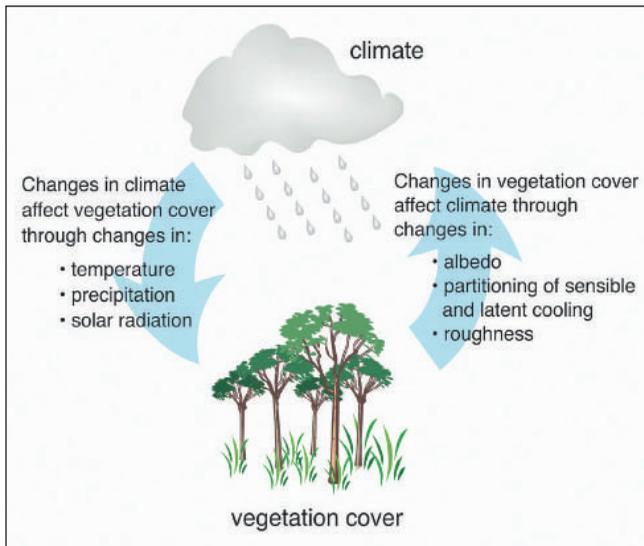


Figure 3. Biophysical feedbacks between climate and vegetation cover. Climate changes can affect vegetation cover through changes in temperature, precipitation, and net radiation. Changes in vegetation cover and surface properties can in turn affect the climate.

their representation of ecological processes (including plant growth and competition, succession, and disturbance) remains somewhat crude.

Levis *et al.* (1999, 2000) used a fully coupled climate–vegetation model to investigate the potential effects of altered vegetation cover on future climate change. They considered global warming scenarios in which vegetation patterns either remained fixed in their current state or were allowed to vary in response to the shifting climate patterns. By comparing the two scenarios, the authors were able to identify

the additional climate variations induced by changing vegetation – the “vegetation feedback” on global warming. They demonstrated that changes in vegetation cover could substantially amplify global warming in high northern latitude regions, through a positive feedback process involving several steps (Figure 4):

- (1) Increases in greenhouse gases warm the planet, especially in the high northern latitudes.
- (2) As the high latitudes begin to warm, the evergreen-dominated boreal forests of North America and Eurasia move northward, replacing treeless tundra.
- (3) The expansion of evergreen forests, which are much darker than tundra (especially in the snowy winter and early spring), causes a significant decrease in albedo.
- (4) The darker forest cover absorbs more sunlight than the tundra, warming the region even more (Bonan *et al.* 1992; Foley *et al.* 1994).

According to Levis *et al.*, a doubling of atmospheric CO₂ would warm landmasses between 45° and 90° N latitude by about 3.3 °C in the spring, even without the vegetation feedbacks, which would increase the warming by an additional 1.1–1.6 °C. While the impacts of vegetation feedbacks on global warming may be localized, they are nonetheless important to helping us understand the future of the climate system.

■ Biogeochemical feedbacks on global warming

Terrestrial ecosystems may also affect the climate by changing the amount of CO₂ in the atmosphere. These biogeochemical feedbacks occur as a result of the two-way interac-

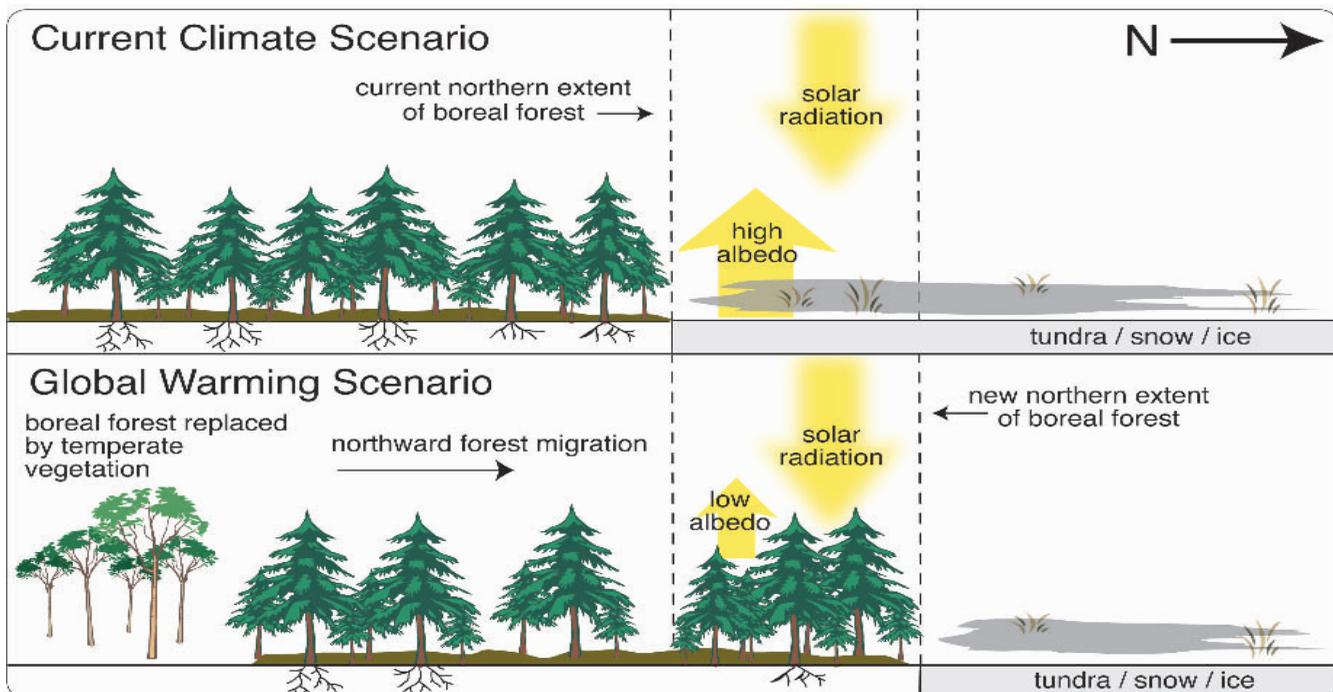


Figure 4. Vegetation feedbacks on global warming.

tion between climate and terrestrial ecosystems (Figure 5). In particular, global warming could affect the ability of terrestrial ecosystems to process C through photosynthesis and respiration and store it in biomass and soil organic matter. Such climate-induced changes in terrestrial C storage may affect the amount of CO₂ in the atmosphere and, as a result, create a feedback effect on the climate.

In the 1990s, humans were releasing roughly 6 billion tons of C into the atmosphere annually by burning fossil fuels (Marland 2000), and another 1–2 billion tons through the burning associated with deforestation (Bolin *et al.* 2000; Houghton 2000). This C becomes CO₂ in the atmosphere. The other half is – temporarily at least – absorbed by the oceans and the terrestrial biosphere (Rayner *et al.* 1999; Bousquet *et al.* 2000; Prentice *et al.* 2001; Schimel *et al.* 2001).

As we continue to pump more CO₂ into the atmosphere, we should remember that the terrestrial biosphere and the oceans may not always be able to absorb such a large amount of our emissions. What if the terrestrial biosphere suddenly stopped absorbing so much CO₂ – or actually started releasing it instead?

The amount of C absorbed by the biosphere is the difference between how much C plants absorb through photosynthesis and how much is released to the atmosphere by plant and microbial respiration. In addition, natural disturbances such as fire, blowdowns, insect outbreaks, and human-caused alterations in land cover, can dramatically alter terrestrial C storage. Generally speaking, these events tend to release C from terrestrial ecosystems. Long-term changes in land use will therefore affect the net C balance.

The terrestrial biosphere appears to have acted as a net C sink for the last few decades, absorbing roughly 1.4 billion tons of C per year in the 1990s, or about 22% of anthropogenic emissions (Prentice *et al.* 2001; Schimel *et al.* 2001). Will this continue in the future, as climatic variations become more pronounced? Changes in climate and atmospheric CO₂ concentrations are likely to alter many aspects of the terrestrial C balance by affecting the rates of photosynthesis, respiration, vegetation mortality, and disturbance.

Two recent modeling studies have shown how this might occur. Research by the UK Hadley Center (Cox *et al.* 2000) suggests that global warming could cause the biosphere to switch from being a net sink to a net source of CO₂. In their simulation, global warming causes a large reduction in rainfall over the Amazon, which causes a severe dieback of tropical rainforests by

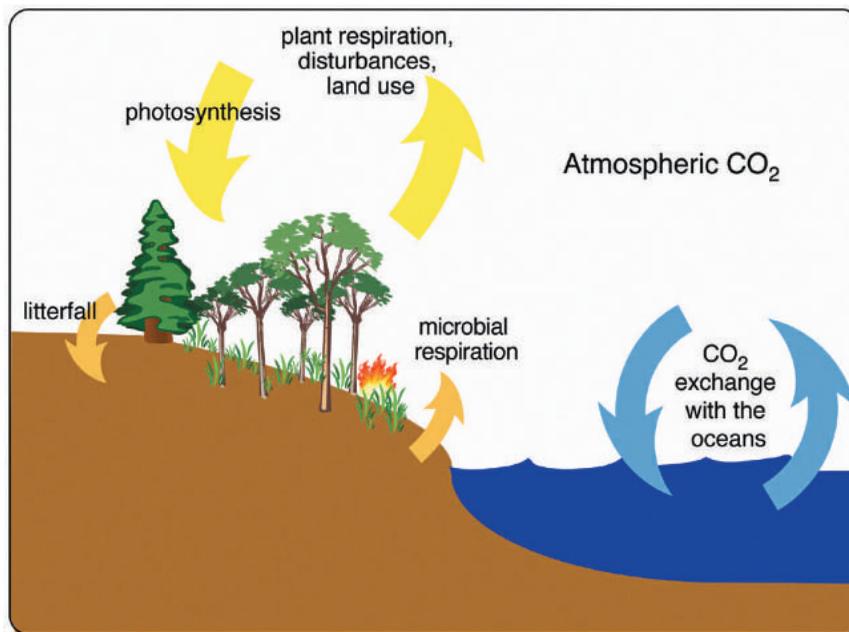


Figure 5. Changes in the C cycle of terrestrial ecosystems directly affect the atmosphere. Currently, the terrestrial biosphere is a net sink of atmospheric CO₂. Variations in climate and atmospheric chemistry, however, could alter this process. The terrestrial biosphere absorbs CO₂ through photosynthesis and accumulates C in living biomass. Some is released back to the atmosphere through plant respiration, and the rest is used to build biomass. Eventually the vegetation dies and enters the detritus and soil C pools. Decomposer microbes release CO₂ back into the atmosphere.

around 2050. Combined with increasing losses from soil organic material, this dieback releases CO₂ back into the atmosphere and further accelerates global warming. Overall, the simulation indicates a global average temperature increase of 4 °C (global warming alone with no feedback from terrestrial ecosystems) to 5.5 °C (including the feedbacks).

Another modeling study obtained qualitatively similar (although less dramatic) results. Friedlingstein *et al.* (2001) showed that global warming could reduce the ability of the biosphere to absorb CO₂ by as much as 25%. In this study, the biosphere did not become a net source of C, but still became much less efficient at absorbing it.

While these results differ in the details, the central message is clear. The amount of CO₂ in the atmosphere will be determined not only by human activity, but also by the terrestrial biosphere and the ocean. Global warming could be substantially accelerated in a warmer world with more CO₂, if the terrestrial biosphere cannot absorb as much CO₂, or terrestrial ecosystems start releasing it from dying vegetation.

■ Conclusions

As we consider the future of the climate and how it may be affected by human activities, we must remember that the atmosphere does not operate in isolation. It is also affected by the ocean and by terrestrial ecosystems. We

are beginning to realize that the biosphere exerts considerable control over the physical systems in the atmosphere and the ocean. A new generation of climate models that allow for the two-way interactions between physical and biological systems is starting to show how important these processes are.

The role of the biosphere cannot be ignored when forecasting the possible climatic changes of the century. We must take into account the potential for ecological feedbacks on climate, which may enhance or reduce the effects of global warming. So far, however, only a few exploratory studies have considered whether changes in the biosphere could affect global warming. At this stage, it is impossible to come to any general conclusions about the magnitude and implications of these feedbacks. It is intriguing to note, however, that the studies published to date suggest that ecological processes would amplify the warming caused by greenhouse gases, not reduce it.

These studies provide a powerful motivation to further examine the interaction between climate and the biosphere. In particular, we must reevaluate future scenarios of global change to consider the potential for vegetation feedback mechanisms. For example, scenarios of CO₂-induced global warming, already amplified in the high latitudes by snow and sea-ice feedbacks, may be substantially modified by long-term changes in the boundaries of evergreen forests and tundra. Furthermore, several GCM simulations have indicated that continental interiors may become much drier in response to global warming, but this prediction does not take into account the potential feedbacks caused by alterations in vegetation cover. Clearly, models used to simulate the future climate must be improved to take into account variations in ecosystems, and their consequent feedbacks on the atmosphere.

Future research efforts should be concentrated along several lines. First, the research community must continue to develop fully coupled models of climate and terrestrial ecosystems, which will allow us to explore the interactions between atmosphere, oceans, ice, and the terrestrial biosphere. Many modeling groups are already moving in this direction, but a range of models would ideally be used, including simple analytical models, earth system models of "intermediate complexity" (simpler, computationally efficient climate models), and the highly complex and computationally expensive global climate models.

We must also put more effort into measuring the effects of terrestrial ecosystems on climate. For example, can we document the effects of land-use and land-cover change on climate? Can we see biophysical vegetation feedbacks operating in the current climate system, on seasonal or multi-year timescales? Can we monitor long-term changes in terrestrial C storage, and how terrestrial ecosystems respond to long-term climate changes?

Finally, policy analysts must determine how important the uncertainties ecological processes introduce into future climate scenarios ultimately are. How will these uncertain-

ties play out in the policy arena, and how are they viewed through the lens of the "precautionary principle"?

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