CLIMATE CHANGE:

Managing Forests After Kyoto

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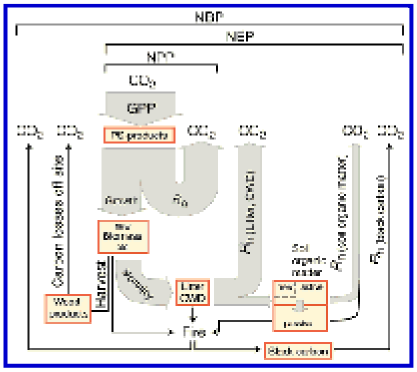
The global carbon cycle is characterized by large natural fluxes into and out of oceans and terrestrial vegetation. These fluxes result in a small net sink (meaning that carbon is absorbed from the atmosphere into land and oceans), which partly compensates the anthropogenic fossil fuel emissions that are the main carbon source for the atmosphere today (1, 2). In view of the likely climatic effects of increasing CO_2 concentrations, the Kyoto protocol was negotiated with the aim of reducing fossil fuel emissions. The protocol also suggests that management of natural terrestrial carbon sinks, primarily afforestation and reforestation at a global scale, can increase sink strength and thus reduce atmospheric CO_2. In the following, we discuss problems associated with the definition of carbon sinks and analyze consequences of fire and harvest in relation to forest stand age. In contrast to the sink management proposed in the Kyoto protocol, which favors young forest stands, we argue that preservation of natural old-growth forests may have a larger effect on the carbon cycle than promotion of regrowth.

The Kyoto protocol evoked an unprecedented effort in biogeochemical sciences. As nations were asked to verify the anthropogenic contribution to the terrestrial carbon sink at scales ranging from plots to continents, large uncertainties emerged. Continental-scale carbon fluxes estimated from forest inventories, eddy flux measurements, and atmospheric inverse model studies led to conflicting results when compared for the same region. For example, sink estimates range between 0.2 and 1.3 gigatons per year (Gt/year) for the continental United States (3, 4), between 0.01 and 1.3 Gt/year for Siberia (5, 6), and between 0.2 and 0.4 Gt/year for Europe (7, 8). These uncertainties arise from the fact that the different methods measure different fluxes of the terrestrial carbon cycle at different temporal and spatial scales.

The carbon cycle can be classified into the following fluxes (see the first figure) (9): gross primary production (GPP; carbon assimilation by photosynthesis ignoring photorespiration), net primary production (NPP; the fraction of GPP resulting in growth when plant respiration, R_a, is taken into account), net ecosystem production (NEP; taking the annual budget of heterotrophic respiration of soil organisms, R_h, into account), and net biome production [NBP; taking nonrespiratory losses such as fire and harvest into account (10)].



Schematic representation of the terrestrial carbon cycle. Arrows indicate fluxes; boxes indicate pools. The size of the boxes represents differences in carbon distribution in terrestrial ecosystems. CWD, coarse woody debris; R_h, heterotrophic respiration by soil organisms; PS, photosynthesis.

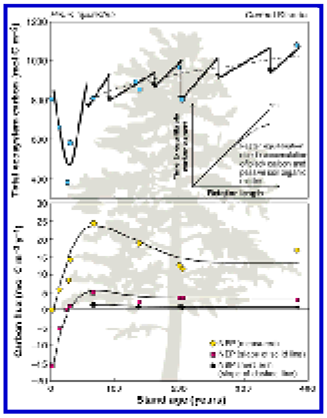
Definitions of these carbon fluxes are based on annual budgets. This is convenient for GPP and NPP, which are input fluxes that are well-defined at an annual scale. But the terrestrial carbon cycle is a highly dynamic system. Especially at the decomposition side of the cycle, there are intermediate pools that differ in their turnover time and "shortcuts" where carbon may return to the atmosphere at a higher pace. Carbohydrate pools turn over on a daily basis, leaves may stay for several seasons, living wood and soil organic matter may persist for millennia depending on species and environment (for example, more than 4000 years in the wood of Bristlecone Pine), and fire may return carbon to the atmosphere instantaneously, although it also produces long-lived black carbon.

NEP (= GPP - R_a - R_h) captures all changes in ecosystem carbon that result from the balance of physiological processes of plants and microbes. Being more variable, respiration rather than assimilation determines the net budget (11). NEP can be detected as changes in biomass, litter, and soil organic carbon (12) in the absence of fire and harvest and is thus not exclusively associated with changes in the passive carbon pool. In forest ecosystems, most carbon is stored in intermediate pools containing materials like wood, litter, or partially decomposed organic matter that range in their degree of chemical reduction somewhere between newly assimilated sugars and almost inert black carbon. All these materials potentially support future respiration and may be preserved or activated by external forcing affecting the physiological balance and therefore NEP. This can result from short-term climatic fluctuations or from long-lasting effects of disturbances that redistribute carbon between pools of different turnover times, for example, converting living into dead biomass or transfer soil carbon from the passive into the active pool.

In NBP, fire and harvest return carbon to the atmosphere or export carbon instantaneously. These pulse-like events override a short-term balance. Ground fire or thinning operations may export a fraction of the living biomass or the organic layer, whereas stand-replacing fires or a full harvest may reset the vegetation to an early stage of succession.

Annual NEP and NBP budgets thus represent a sum of many disparate pools of the carbon cycle, and interpretation of measured flux rates is difficult. It appears that only large-scale inventory studies that include not only biomass but also coarse wood debris and the organic layer can capture the stochastic effects of disturbance (13), and it remains unclear why inventory studies result in lower estimates of the terrestrial sink than inverse models.

Consider, for example, the changes in carbon pools of a boreal pine forest of Siberia following a stand-replacing fire (see the figure below). The total carbon pool of a stand decreases in young stands because decomposition of dead biomass from the previous forest generation results in respiration that is higher than the NPP of the regrowth. In a boreal forest, it takes decades for NPP to exceed R_h. The carbon pool then increases rapidly until canopy closure. In contradiction to the ecological equilibrium paradigm, the total carbon pool continues to increase even in old stands. In boreal forest, this trend of carbon accumulation is interrupted by repeated ground fire (in managed forests by thinning), which results in a "sawtooth"-type time response (see the top panel in the figure below).



Age matters. Changes of total ecosystem carbon (**top**) and of NPP, NEP, and NBP fluxes (**bottom**) with stand age in Siberian pine stands. The sequence starts and ends with a stand-replacing fire. The "sawtooth" dents in total ecosystem carbon result from repeated surface fires. Downward arrows indicate carbon losses caused by these fires. The stands accumulate carbon between fires at a rate indicated by the upward slope of the "dents," which represents NEP. The slope of the dashed line indicates the short-term NBP, including fire losses. The carbon loss decreases initially because the respiratory losses caused by decomposition of coarse wood debris left over from the preceeding forest generation are higher than the carbon uptake of the young regrowing forest. Inset in top panel: Time to equilibrate carbon export by fire or harvest in relation to the life-span of the forest stand (stand-replacing fire cycle or rotation period). Under constant conditions, the time required to equilibrate carbon exports should be equal to the rotation period (1:1 line). However, with increasing life-span of the stand, proportionally more carbon can be transferred into a permanent pool of soil carbon (passive soil organic matter or black carbon). Therefore, the time for equilibration decreases with increasing rotation length, because more carbon is generated that cannot be exported. Data from (15).

Long-term changes in carbon stocks at plot scale generally ignore the main carbon loss that takes place with stand-replacing fires (or final harvest). How long it takes to equilibrate this loss depends on the initial amount of carbon exported by fire or harvest. A fire in a young stand (or a harvest of a fast rotation forest) will export less carbon and can be equilibrated faster than a fire in an old stand or the harvesting of long rotation managed forest. Under constant conditions of resource supply and climate, it will take about the same amount of time to replace the exported biomass as it took to grow it (see inset in top panel in the figure above). There is thus no difference between short and long rotations, except that old stands allow more carbon to enter a permanent carbon pool. This is because the permanent turnover of leaves and roots will contribute to the active and persistent pool of soil organic matter, and depending on age, ground fires will contribute to the formation of black carbon, so that with each rotation (by full harvest or stand-replacing fire), soil organic matter and black carbon are accumulated. The fraction set aside in this way increases with rotation length. Monitoring Kyoto forest plots over short periods of time will tend to overestimate carbon storage.

Two major questions emerge: Is an equilibrium of assimilation and respiration at the plot or landscape scale possible? And are forested landscapes different in their sink capacity depending on whether they have old-growth forest or young fast rotating stands (not taking into account the large carbon loss caused by the reduction of the landscape carbon pool associated with a shortening of the rotation length)?

These questions cannot be answered with certainty yet, but an increasing number of process studies indicate that terrestrial forest ecosystems do not reach an equilibrium of assimilation and respiration and act as net carbon sinks until high ages (14). We believe that this is because the carbon cycle of forests is driven by the turnover of leaves and roots, which will continue to contribute to a stable part of soil organic carbon unless disturbed by harvest or fire. We also hypothesize that the accumulation of carbon in a permanent pool increases exponentially with stand age, because time without disturbance is required to channel carbon through its cycle into a nonactive pool of soil organic carbon and the production of black carbon depends on biomass.

These arguments indicate that replacing unmanaged old-growth forest by young Kyoto stands, for example, as part of a Clean Development Mechanism or during harvest of previously unmanaged old-growth forest stands as part of forest management (the latter does not gain credits under the Kyoto protocol), will lead to massive carbon losses to the atmosphere mainly by replacing a large pool with a minute pool of regrowth and by reducing the flux into a permanent pool of soil organic matter. Both effects may override the anticipated aim, namely to increase the terrestrial sink capacity by afforestation and reforestation.

References and Notes

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