COMPARING THE IMPACTS OF DIFFERENT DISTURBANCES OF WESTERN NORTH AMERICAN FORESTS ON CARBON CYCLING

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ABSTRACT
Two major disturbances of forests in western North America are fires and insect outbreaks. Much research has focused on the effects of fires on the carbon cycle; little research to date has occurred about outbreaks. We are using observations, including field measurements and remotely sensed imagery, together with ecosystem and insect population modeling improve our understanding of these disturbances on carbon cycling.

INTRODUCTION
Time since disturbance is a major control on whether a forest ecosystem is a carbon source or sink. Fires and insect outbreaks are the major natural disturbance of western North American forests. Although these two disturbances have high interannual variability, on average a similar amount of forest is affected annually in North America by each disturbance *(0.4-4 million ha per year; Leenhouts 1998, Houghton et al.* 2000, USDA Forest Service 2004).

Insect outbreaks and fire have similar impacts on carbon cycling, yet differences also exist. Both disturbances kill substantial numbers of trees. Trajectories of carbon stocks are expected to be similar: a reduction in living biomass and an increase in dead wood immediately following the disturbance, followed by a slow recovery of living stocks. Differences have yet to be quantified but are expected to be important. Fires combust a substantial fraction of carbon in the form of foliage, twigs, and surface litter, resulting in a large, immediate pulse of carbon to the atmosphere. Bark beetle outbreaks, in contrast, leave all the biomass for decomposition. Crown fires kill all trees, including young and old, whereas beetle outbreaks typically affect older trees of the host species, leaving behind younger and non-host trees. In some cases, outbreaks cause increases in tree-level productivity as younger trees are released from competition.

EFFECTS OF FIRES ON CARBON BUDGETS
Extensive research has focused on the effects of fires on the carbon cycle. Here we present several examples of our studies. We have measured carbon stocks and fluxes along a chronosequence of lodgepole pine forests in Yellowstone National Park to characterize the initial dynamics following fire as well as defined the longer term recovery process. We found that the net ecosystem flux is strongly negative for several years following the fire. By 35 years, however, the forests switch from a carbon source to a carbon sink. The net carbon sink flux is lower than the net carbon source, but extends for several hundred years. At 236 years following the fire, the forest has re-assimilated all the carbon lost in the fire.

Fires have also been studied using remotely sensed imagery. For example, we analyzed post-fire dynamics using a 17-year record of satellite-derived net primary production (NPP) in boreal North America. We found a rapid recovery of NPP, with values returning to prefire levels within nine years on average.

DIFFERENT EFFECTS OF OUTBREAKS

In contrast to work on fire, little research to date has occurred concerning outbreaks and carbon cycling. The more diffuse nature of outbreaks within an infestation implies difficulty in quantifying affected area and biomass compared to fire and in establishing chronosequences for field study. For example, burned area is easier to detect from satellite remote sensing than outbreaks as a result of the presence of thermal anomalies and more extensive biomass removal. Significant feedbacks exist between insect outbreaks and climate, fire, and forest characteristics that influence carbon stocks and fluxes. Because mountain pine beetle outbreaks are governed by temperature, they are sensitive to future warming. Changes in fire regime will lead to shifts in mean stand age, another important forest variable influencing outbreaks.

Our team is involved in several activities to increase understanding of mountain pine beetle outbreaks in North America. We have run a model of insect outbreaks driven by temperature to historical and projected climate in the western United States. Total area suitable for outbreak is reduced with future warming, though at higher elevations, initial increases in suitable area will occur. Just as for fire regimes, changing insect outbreak regime in response to climate change have important consequences for stand ages and therefore for carbon budgets.

We are also quantifying landscape-scale characteristics of insect outbreaks with aerial detection survey (ADS) maps and remote sensing imagery. Though subject to uncertainty, the ADS maps provide a substantial amount of useful information for studying carbon cycling, such as area affected, insect species, and host species over many years. We are using Quickbird multispectral imagery (2.44-m spatial resolution) to quantify mountain pine beetle outbreak extent at high elevations in Idaho. These fine-resolution data will allow us to characterize the patchiness of outbreaks, leading to an understanding of required spatial resolution for use in detection, monitoring, and modeling. In addition, we are evaluating MODIS imagery for its ability to study widespread outbreaks. Although much coarser resolution than Quickbird data, the 500-m MODIS reflectances have global coverage twice daily, an advantage for studying continental-scale carbon cycling.