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Sink or Source? Fire and the Forest Carbon Cycle

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Joint Fire Science Program

Fire Science Brief

RESEARCH SUPPORTING SOUND DECISIONS

Lodgepole pine regenerates among standing dead in Yellowstone National Park after the 1988 fires. Credit: Jim Peaco.

Sink or Source? Fire and the Forest Carbon Cycle

Summary

As the size and severity of fires in the western U.S. continue to increase, it has become ever more important to understand carbon dynamics in response to fire. Many subalpine forests experience stand-replacing wildfires, and these fires and subsequent recovery can change the amount of carbon released to the atmosphere because subalpine forests store large amounts of carbon. Stand-replacing fires initially convert ecosystems into a net source of carbon as the forest decomposes—a short-term effect (decades) that will likely be important over the next century if fire frequency increases as a result of climate change. Over the long term (centuries), net carbon storage rebounds throughout the fire cycle if forest stands replace themselves. In a case study of the landscape changes resulting from the 1988 fires in Yellowstone National Park, landscape carbon storage was shown to be resistant in the long term to changes in fire frequency because the most rapid changes in carbon storage occur in the first century, these forests regenerate quickly, and the current fire interval is very long. In subalpine ecosystems with different characteristics, however, the conversion of forest to sparse forest or meadow after fire is possible and could have a large impact on landscape carbon storage.

Key Findings

- In a landscape characterized by a natural stand-replacing fire regime, the ability of that landscape to store carbon will change only minimally over the long term—as long as the forest regenerates after fire.
- The carbon lost in the 1988 Yellowstone fires and in the subsequent biomass decomposition will be recovered quickly relative to the current fire interval.
- Carbon storage on the Yellowstone National Park landscape would be reduced only if stand-replacing fires become much more frequent than is projected.

The carbon cycle: A refresher

First, a brief review of the basics. In simplistic terms, plants take up carbon dioxide (CO_2) from the atmosphere through photosynthesis and create carbohydrates that animals and humans use for food, shelter, and energy to sustain life. Emissions from plants and human activities return carbon to the atmosphere—thereby completing the cycle. Carbon cycles through the system and moves between reservoirs. The balance of carbon exchanges between the reservoirs makes up the carbon budget. When the inputs to a reservoir exceed the outputs, the amount of carbon in the reservoir is increased, and it is considered a carbon "sink"—a place where carbon is stored (or sequestered). When the outputs from a reservoir exceed the inputs, it is considered a carbon "source"—a place from which carbon is emitted. Non-atmospheric sinks are important for offsetting carbon emissions and preventing (or at least slowing) global warming. Investigating the factors affecting sources and sinks can inform management decisions aimed at getting us closer to a balanced carbon budget.

Let's next briefly review the interactions specifically between forests, fire, and carbon. Forests have a life cycle: trees die after disturbance, such as a stand-replacing fire, setting the stage for new growth to begin. If a forest fully replaces itself, there will be no net carbon change over that life cycle. The fire consumes only about 10 to 20 percent of the carbon and immediately emits it back into the atmosphere. It kills trees but doesn't consume them. So, new trees grow (storing carbon), old trees decompose (emitting carbon), and the organic layer of the soil accumulates (storing carbon). This balance between simultaneous production and decomposition determines whether the forest is a net source or sink. The net ecosystem carbon balance, also known as net ecosystem production (NEP) specifically quantifies the annual net change in carbon stored in the ecosystem. And that's the "magic number," so to speak, needed to gauge whether a forest is a carbon source (negative NEP) or sink (positive NEP) at any given point in time. NEP is often quantified on an annual basis and for a single forest stand. But to determine whether an entire landscape (which is composed of many stands of different ages) is a carbon source or sink over a longer time frame, annual NEP must be assessed over both space and time.

The forest's role and fire's effects

Coniferous forests contain more than one-third of all carbon stored on land. Forests and long-lived wood products currently offset approximately 340 million tons (310 million metric tons) of U.S. fossil fuel emissions of carbon, an estimated 20 percent of the total. This ecosystem service cannot be overstated. Dr. Michael G. Ryan, Research Ecologist with the Forest Service, Rocky Mountain Research Station, illustrates: "Just to give you an idea of how big that number is, to reduce our emissions by another 10 percent, we would have to convert every automobile in the United States into something that gets hybrid fuel economy…like 50 miles to the gallon. Every car."

On the other hand, stand-replacing fires account for a sizeable amount of carbon emitted back into the atmosphere. Consider this in light of the fact that current climate models predict the area burned in the United States to increase by 25 to 50 percent over the next hundred years. We therefore need to examine the short- and long-term effects of these fires to be able to predict the carbon balance over the next century and more accurately estimate future changes in the global carbon budget over the next several centuries. In this article, we'll first explore the basic interactions that take place in subapline forests within the first century post-fire and those that occur over the long term (several centuries). We'll then take it to the ground and look at research conducted in Yellowstone National Park that investigates both the short- and long-term effects of the 1988 fires.

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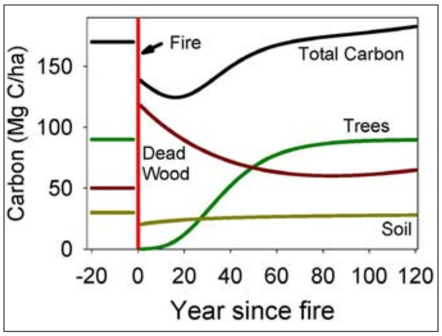
The short and the long of it

Immediately after a fire, carbon is lost to the atmosphere through combustion. Stand-replacing fires kill living biomass in forests and reduce carbon gains to near zero. The strongest effect of fire on carbon cycling, however, occurs in the changing balance between carbon lost through subsequent decomposition and simultaneous carbon gains through growth of new vegetation. In fact, the decomposition of dead biomass that lasts for several decades post-fire can release up to three times as much carbon as that lost in the initial combustion. And during this period, carbon lost through decomposition exceeds the carbon accumulating in regrowth. Then, as the forest continues to reestablish and decomposition tapers off, carbon storage in trees eventually "catches up," and the carbon balance of loss and gains approaches an NEP of zero. According to Dr. Ryan, "In 30 to 40 years or so of regeneration, you cross the positive line because growth and accumulation is out-pacing the decomposition of the dead matter. And then in approximately 80 to 100 years, the ecosystem has recovered completely to pre-fire carbon levels." So in the short-term, over the time frame of the first century post-fire, stand-replacing fires convert the landscape into a carbon source and then back into a carbon sink.

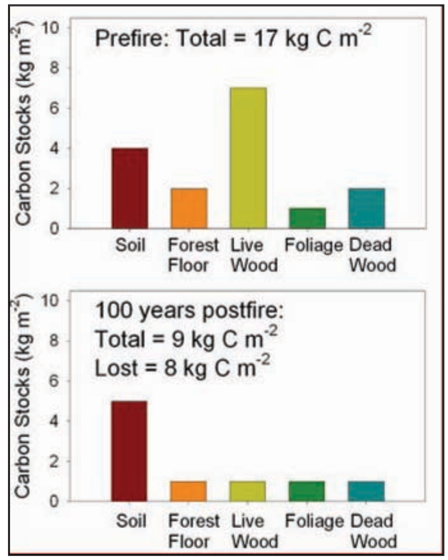


Hypothetical pattern of forest carbon through a fire cycle with tree regeneration, including carbon in dead wood, in soil, and in live trees. On-the-ground research shows that carbon recovery occurs in approximately 80–100 years if the stand regenerates.

Long-term effects of fire (over centuries) on the carbon balance depend on post-fire regeneration and fire frequency. We see a large difference in the ability to recover pre-fire carbon storage levels between stands having low initial regeneration and those that replace biomass quickly. The take-home message here is that the replacement of biomass for a given stand over multiple fire intervals plays *the* critical role in the relationship between fire and the carbon balance. If, as a result of crown fire, a forest converts to grassland or meadow rather than regenerating, much carbon can be lost from the ecosystem. Dr. Ryan emphasizes the point: "Regeneration is absolutely critical to carbon. If you don't get regeneration, the ecosystem loses about half of its carbon." But if the forest *does* regenerate—and exists on the landscape long enough before the next stand-replacing fire—it will recover the carbon lost over the fire cycle.

A natural laboratory: The Yellowstone landscape

To conduct their study—funded by the Joint Fire Science Program—of short- and long-term changes in carbon storage resulting from stand-replacing fires, the research team headed to the landscape of Yellowstone National Park. Fire frequency in the park ranges from 200 to 300 years, and in 1988 approximately 620,000 acres (250,000 hectares) of lodgepole pine burned. This particular landscape was chosen primarily because all the components of the carbon cycle were present (that is, no wood had been removed). It is important to note that, although specific results of this research do not necessarily apply to all subalpine ecosystems, the results can inform further investigation in other subalpine forests with different ecological characteristics and fire regimes.

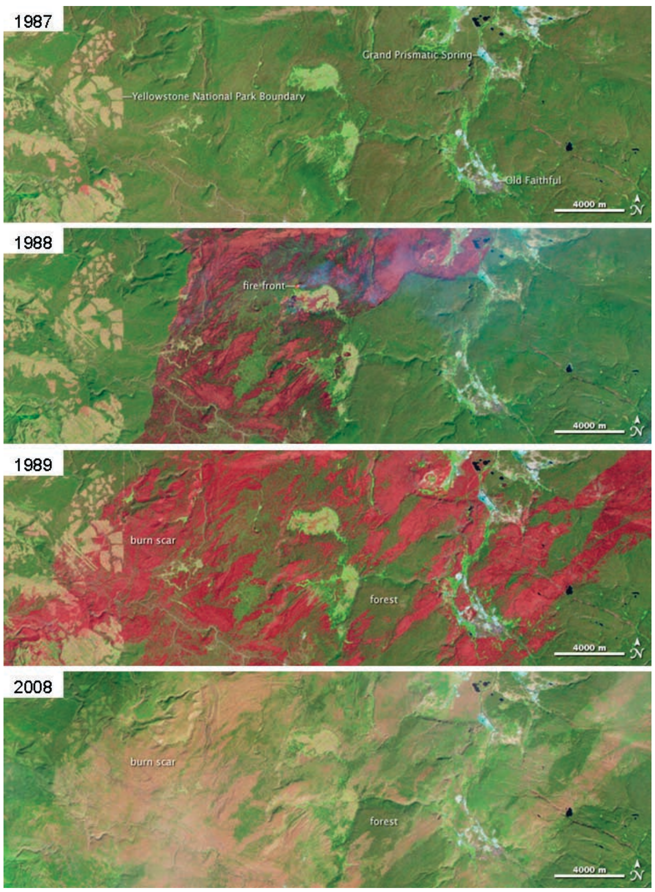


Hypothetical carbon distribution before and a hundred years after a crown fire with no regeneration. If the forest is replaced by meadow or shrubland, carbon stored in the ecosystem will be lower.

1988 Crown fire approaching Old Faithful Photo Shop & Snow Lodge in Yellowstone National Park.

Short-term effects of the '88 fires

The team modeled the recovery of carbon storage in Yellowstone to estimate landscape changes in carbon balance for 250 years following the 1988 fires. The researchers used published estimates of carbon levels in the kinds of mature lodgepole pine stands that burned and, from these data, predict that the landscape will act as a large but short-lived carbon source followed by a long period in which it will serve as a moderate carbon sink. The NEP of the landscape as a whole is currently negative and should remain so for approximately 35 years post-fire while decomposition is high. The team estimates that the Yellowstone landscape will reach positive NEP values (becoming a carbon sink) about 40 years post-fire, and that the total carbon lost will be recovered completely within approximately 80 to 100 years after the fires. In addition, results from the Century model (which uses climate information to predict carbon, water, and nutrient cycles), suggest that over the next hundred years temperature and precipitation will increase in the Yellowstone ecosystem, thereby increasing forest growth rates. It follows that these predicted increased growth rates will lead to more carbon stored as well as quicker recovery of carbon after fire. It is important to note here that, although the data point to quick carbon recovery relative to the length of the fire cycle, these results are not useful for understanding the effects of climate change on landscape carbon storage at the shorter timescales. Fires similar in size and severity to the 1988 Yellowstone fires would have a large effect on the global carbon budget over the next half century, regardless of the ability of individual landscapes to recover carbon loss over the next few centuries.



Landsat-5 satellite images tracking one fire in Yellowstone and the landscape's gradual recovery. Darker red areas are the most severe burns. Twenty years post-fire, the forest had started to return. Credit: Images courtesy of the National Aeronautics and Space Administration (NASA).

Long-term effects of the '88 fires

To evaluate their hypothesis that climate change will likely alter fire frequency and result in changes to the landscape that would affect carbon storage, the scientists applied the fire modeling results of a previous study to simulated carbon budgets on the Yellowstone landscape. They compared carbon stored on an approximately 200,000-acre (80,000-hectare) area under three scenarios: 1) the current fire frequency based on 20th century data, 2) an increased (approximately 12 percent) fire frequency resulting from a dry-climate simulation, and 3) a decreased (20 percent) fire frequency resulting from a wet-climate simulation.

The research team was surprised to find that none of the various fire frequencies of these different climate scenarios had any sizeable effect on carbon storage, suggesting that landscape carbon storage is resistant to large changes in stand density or age distribution. So by extension, it would take a major type conversion—such as from forest to non-forest (that is, lack of regeneration)—to produce a considerable change in carbon storage on the landscape.

This finding leads to the question: What *would* it take to cause such a drastic type conversion that would significantly affect the landscape's ability to store carbon? The short answer is that it depends on the ecosystem. Ryan points to the example of the 2002 Hayman fire in Colorado. That ecosystem, primarily montane forest dominated by ponderosa pine, historically experienced surface- to mixed-severity fires; however, because of increasing fire size and severity in the western U.S., crown fires raged through the area in 2002. Ryan explains, "Sixty-thousand acres in the middle of the fire had a really big run for a couple of days. There are now no live pockets—nothing there to supply seeds—and the seeds don't survive fire like they do in lodgepole pine. So that area is going to be a meadow for a long time to come."

On the other hand, in the quickly regenerating Yellowstone ecosystem, most change in carbon balance occurs in the first few decades post-fire; therefore, considerable changes in carbon storage would require that fire frequency be shortened to within this window of time. In fact, because the Yellowstone landscape is predicted to recover to pre-fire carbon levels within 80 to 100 years post-fire, the fire interval would need to shorten to, say, less than 50 *years* (from the current fire interval of 200 to 300 years) to significantly reduce carbon storage potential over the long term. Therefore, the investigators conclude that, although it will act as a carbon source in the short term, the Yellowstone landscape will be resilient in terms of carbon storage capability over the long term because of its long fire intervals.

Lodgepole pine cone opened by heat of fire—Yellowstone 1988. Credit: Jim Peaco.

Filling in the gaps

The first State of the Carbon Cycle Report (SOCCR) was published in 2007. The report was funded by the Climate Change Science Program, an interagency entity including (but not limited to) the U.S. Department of Agriculture (USDA), the U.S. Department of Interior, (USDI), and the Emissions Predictions and Policy Analysis (EPPA). The report highlights the fact that "there is insufficient information available to guide land managers in specific situations to change forest management practices to increase carbon sequestration."

First, there is a need for research on carbon storage in ecosystems with surface- or mixed-severity fire regimes, where stand-replacing fires may lead to land cover conversions that could move the carbon from the forest to the atmosphere—possibly for centuries. Second, the landscape effects of fuel treatments on forest carbon storage need to be investigated. To fully understand the carbon consequences of fuel treatments requires a landscape-scale study of current and projected fire intervals as well as information on regeneration. And Dr. Ryan specifically emphasizes the need for regeneration research: "I think that's the thing we need to be looking at next. We [the Forest Service] don't have a good sense of how this last decade of fires has actually regenerated. We need to conduct a broad-scale study in a number of different forest types. We need to know what the probability of regeneration really is. Do we have a problem in this area or don't we?" By continuing to work towards understanding these (among other) unknowns surrounding the interactions of forests, fire, and carbon, we can better refine our management strategies to realize significant carbon sequestration in accord with other land management practices aimed at improving the health of our forests.

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Management Implications

- The most valid means by which to manage forests for carbon sequestration are 1) keeping forests as forests, 2) reforesting areas where forests historically occurred, 3) using forest biomass to offset fossil fuel use, and 4) promoting long-lived forest products such as wood-framed buildings.
- Forests, especially older forests, generally store carbon better than forest products, so harvesting older forests for forest products is not an effective carbon conservation strategy.
- In forests having surface- and mixed-severity fire regimes, managing for maximum carbon storage will lead to an increase in stand density and thus the probability of more severe fires. On the other hand, managing to reduce fuels and thus the probability of severe fires will reduce the carbon stored in the forest, and it will likely become a carbon source (unless thinnings are used as biomass fuel in place of fossil fuel).
- Focus post-disturbance management on regeneration.

Further Information: Publications and Web Resources

The First State of the Carbon Cycle Report (SOCCR). 2007. *The North American Carbon Budget and Implications for the Global Carbon Cycle*. http://cdiac.ornl.gov/SOCCR/

Kashian, D.M., W.H. Romme, D.B. Tinker, M.G. Turner, and M.G. Ryan. 2006. Carbon storage on coniferous landscapes with stand-replacing fires. BioScience 7: 598-606.

Smithwick, E.A.H., M.G. Ryan, D.M. Kashian, W.H. Romme, D.B. Tinker, and M.G. Turner. 2009. Modeling the effects of fire and climate change on carbon and nitrogen storage in lodgepole pine (*Pinus contorta*) stands. Global Change Biology 15: 535-548.

Scientist Profile

Mike Ryan is a Research Ecologist with the Forest Service, Rocky Mountain Research Station. He has over 20 years of research experience in the ecophysiology of forests and factors influencing carbon exchange and accumulation. His intensive research sites have included temperate forests (Colorado, Wyoming, and Oregon), boreal forests (Canada), and tropical plantations and native forests (Costa Rica, Brazil, and Hawaii). He received his PhD from Oregon State University in 1987 and conducted his post-doctoral work with the Ecosystems Center at Woods Hole (MA).

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