Joint Fire Science Program
Fire Science Digest
RESEARCH SUPPORTING SOUND DECISIONS

ISSUE 12 FEBRUARY 2012

Bark Beetles and Fire:
Two Forces of Nature Transforming Western Forests

Bark beetles are chewing a wide swath through forests across North America. Over the past few years, infestations have become epidemic in lodgepole and spruce-fir forests of the Intermountain West. The resulting extensive acreages of dead trees are alarming the public and raising concern about risk of severe fire. Researchers supported by the Joint Fire Science Program (JFSP) are examining the complicated relationship between bark beetles and wildfire, the two most influential natural disturbance agents in these forests. Are the beetles setting the stage for larger, more severe wildfires? And are fires bringing on beetle epidemics? Contrary to popular opinion, the answer to both questions seems to be "no."

Dana Hicks

Mountain pine beetles attack a lodgepole pine tree in British Columbia.

A widely discussed new paper stemming from a JFSP project maintains that a beetle-killed lodgepole pine or spruce-fir forest will probably burn no more severely than a comparable green forest, because wildfires in this system are driven primarily by climate (in the long term) and weather (in the short term), and not by fuels. In fact, in the short term, beetles may be reducing canopy fuels that could feed a crown fire. Other findings from the same project indicate that, even though burned trees may attract more beetles, wildfire does not seem to be promoting the beetle epidemic.

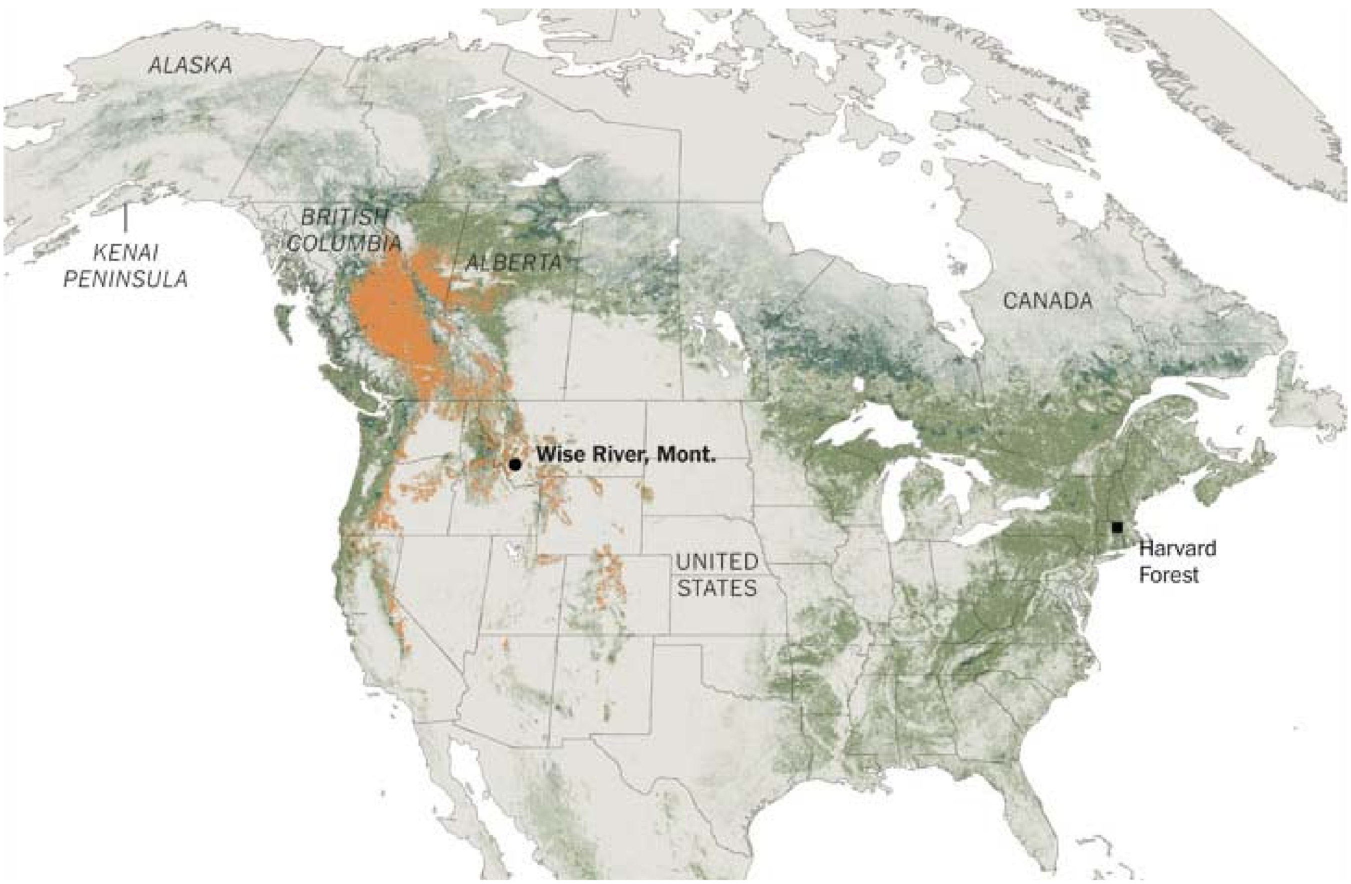
However, not everyone is convinced. Observations of fire managers suggest that beetle damage is increasing risk of severe fire in some places. Moreover, management activities like fuel treatments and prescribed burning have potential to reduce fire severity and extent and dampen beetle epidemics by increasing heterogeneity across the landscape. Additional JFSP-supported research is looking into the effects of salvage logging, prescribed burning, and other management strategies on regeneration, nitrogen cycling, soil and water quality, forest dynamics, and future accumulation of fuels.

The fire-beetle relationship is too complicated to yield easy management conclusions. To intervene effectively, managers must consider their objectives in light of the ecological, economic, and social opportunities and constraints within their management scope and in light of the ecological drivers of both beetle epidemics and wildfire. Finally, climate change complicates understanding of wildfire and beetle epidemics, both of which seem to be responding to a warming climate.

A Big Stage

The lodgepole pine forests of Colorado, Utah, Wyoming, Montana, Idaho, and British Columbia are a big stage for nature's more dramatic acts. Two of the most dramatic are wildfire and bark beetle outbreaks. Historically, fire hits these forests infrequently (every 100 to 300 years), but with stand-replacing severity. In addition, periodic blooms of mountain pine beetles, spruce beetles, and Douglas-fir beetles kill millions of acres of conifers every few decades.

Right now, these beetles are in full-blown epidemic mode. "It's continental in scale, from



Areas in orange were affected by the mountain pine beetle in Canada, 1999–2010, and the U.S., 2005–20 (projected). *Source: http://www.nytimes.com/interactive/2011/10/01/science/earth/forests.html?ref=earth*.

northern Mexico up to northern B.C.," says Dan Tinker, a forest ecologist at the University of Wyoming and co-investigator on a major JFSP-supported study examining the relationship between beetle outbreaks and wildfire. "Nearly everywhere in the Intermountain West has some level of infestation."

Mountain pine beetles and spruce beetles have attacked lodgepole pine and Engelmann spruce over millions of hectares throughout the subalpine zones of the Rockies and have killed between 60 and 80 percent of the mature trees in some places. The dead trees become hosts not only to the beetles, which colonize them to feed and reproduce, but also to microorganisms, other insects, and vertebrate wildlife. As the trees shed needles, die, and eventually fall, they let in sunlight that releases tree seedlings and saplings, shrubs, herbs, and grasses, and the new forest community begins to come together.

Bark beetles are natives to these forests, present in the background all the time. They kill a few trees every year, enough to maintain their numbers during the nonepidemic periods. Even large-scale outbreaks are not uncommon. Tree-ring research since the 1980s has confirmed repeated beetle outbreaks in northwestern Colorado throughout the last half of the 19th century.

While large outbreaks are not unprecedented, the current beetle epidemic may be the biggest ever. Researchers Andrea Brunelle and Steven Munson analyzed lake-pollen deposits in high-elevation spruce-fir forests in Utah (JFSP Project No. 06-3-1-31) and found that the current spruce-beetle outbreak, at least, is bigger than any of those they detected in the pollen record. What is certain is that bark beetles in general are more widespread and severe than at any other time in recent memory. British Columbia, with an extensive forest industry, has been hit particularly hard.

"Some people will say, 'We're losing the forest,'" says Chuck Rhoades, a U.S. Forest Service (USFS) research biogeochemist at the Rocky Mountain Research Station. "But actually, what we're losing is the overstory."

Research by Rhoades and others on postbeetle regeneration indicates that lodgepole pine recovers rapidly after a beetle attack. "It's an early-successional species that responds well to disturbance, and it's not going away. But this is a sort of subtle and esoteric point, and some people get it and some don't. Most people are shocked the first time they see all these red, dead trees."

"With the increased beetle activity right now, these areas are very conspicuous," says Monica Turner, a landscape ecologist at the University of Wisconsin and coauthor of a new paper (Simard et al. 2011). "But it's not a catastrophe from the ecosystem's point of view." Thomas Veblen agrees. "The forests and these beetles coevolved," says Veblen, a geographer at the University of Colorado and a pioneer of research on the fire-beetle relationship. "This epidemic is not an ecological disaster. However, in the areas of resource values, potential impact on forest use, and fire hazard—all these are urgent issues."

What's worrisome about this outbreak is that the beetles are pushing into new territory. Northern British Columbia, for example, is on the extreme edge of the mountain pine beetle's historical range. The beetles have crossed the spine of the northern Rockies, apparently for the first time, and are now resident in Alberta jack pine forests. While they are not yet at epidemic levels there, they may be poised to spread into other pine species across the northern tier of the continent.

Bark beetles have also spread upslope into alpine forests of whitebark and bristlecone pines, where cold temperatures have historically kept them out. Whitebark pine provides an important autumn food source for grizzly bears and habitat for other high-elevation wildlife. Biologists call it a "naive" species as far as bark beetles are concerned, because the tree has little evolutionary experience with the beetles and consequently hasn't developed defense mechanisms. It is doubly vulnerable because it is also susceptible to white pine blister rust, which stresses the tree and makes it more prone to beetle attack. "The presence of bark beetles at these high elevations," Rhoades says, "is a good indication that this outbreak is unprecedented, at least at some elevations and for some [tree] species."

> ***"This epidemic is not an ecological disaster. However, in the areas of resource values, potential impact on forest use, and fire hazard—all these are urgent issues."***

The main factor in these new dynamics, most experts agree, is a warming climate. "Temperatures have warmed in the past 20 or 30 years—the data are consistent on that," says Turner. "We're getting earlier snowmelt, a longer growing season, and milder winters." These developments favor an environment that drives beetles to reproduce more often in a season and allows more larvae to survive the winter.

Coevolutionary Combat

A beetle outbreak begins when a few adults land on a tree. The females burrow under the bark, dig galleries, and lay their eggs. The beetles also introduce friendly fungi that help the larvae digest the tree's tissues. When the larvae hatch, they eat their way through the phloem around the bole, ending their journey by excavating pupal chambers from which the adults emerge. The extensive tunneling girdles the tree and, possibly with assistance from microorganisms, kills it.

Bark beetles can produce the most offspring in mature, healthy trees because they provide ample nutrition for the growing larvae. However, in their coevolutionary combat with beetles, trees have developed chemical and physical defenses to repel attacks. A key weapon is a toxic resin that clogs the initial entry wounds. When beetles are at low, or endemic, levels, healthy trees can fight off the few attackers, so the beetles tend to avoid them, relying instead on highly stressed trees. Unfortunately for the beetles, these trees are scattered, less nutritious, and filled with competitors.

But the beetles have their own counterattack strategies. They emit pheromones that attract more of their own kind. If there are enough beetles in the neighborhood, they come together in a process known as aggregation: an army of beetles overcomes the defenses of the host tree and moves onto the next one. As beetles succeed in colonizing and taking advantage of the nutritional resources of healthy trees, they are rewarded with higher reproductive success and produce many more beetles in succeeding generations.

Sky Stephens

Trees killed by mountain pine beetles on the Medicine Bow National Forest.

If an outbreak crosses certain critical thresholds, it blooms into an epidemic. At that point there's nothing to do but watch it run its course. "Six or eight years ago, we were under a lot of public pressure to stop the beetles from spreading further," says Steve Currey, director of bark beetle operations on the Medicine Bow-Routt National Forests in Colorado and Wyoming. "Now people understand that this thing is too big, and really impossible to stop."

It's a sign of the times when the job title "bark beetle operations" even exists. In Currey's territory, the outbreak started in northwestern Colorado in the mid-1990s and moved northeast to central Wyoming. The Medicine Bow-Routt National Forests now have more than a million acres of beetle-killed lodgepole pine in all stages: infested green, red, gray, and down wood.

"The beetles aren't killing every tree," Currey says, "but they're killing a majority of mature lodgepole. We don't have much ponderosa pine on our forest, but on the Front Range of Colorado they're starting to infest ponderosa pine. And we've lost a lot of limber pine, too." Thankfully, he says, this outbreak seems to be slowing down: on the Medicine Bow the infested area grew by only about 9 percent in 2009 and 2010, down from an 85-percent increase in 2007 and 2008.

An epidemic comes to its natural end either when cold temperatures (minus 40 degrees F or below for several days) kill the larvae and knock the beetle population back or when the beetles run out of host trees to eat. Colonized trees usually die within a year of attack. The following year the needles turn red, and over the next 2 or 3 years they fall to the ground, leaving skeletal gray trunks and branches. After a decade or so, the dead snags topple to the forest floor and lie there amid the beginnings of a renewed forest community.

The new understory growth is evidence that the forest will recover. But for now, the huge swaths of red and gray can be a painful sight for visitors to Yellowstone National Park and throughout the Intermountain West. Viewed from a temporal or spatial distance, the effect is stunning and oddly beautiful. But most people experience a visceral jolt of dismay, followed by a keen sense of loss, followed by heightened alarm about the prospect of wildfires raging through the dead trunks and the living trees springing up under them.

Tangled Relationship

It is well known that wildfires are also on the rise in the Intermountain West. To the casual observer it seems that these disturbances must be linked in a malevolent feedback loop, with fires setting the lunch table for beetles and beetles creating dead fuel that invites future fires. Common sense seems to confirm this: How can all those dead trees not be a tinderbox? How can they not attract further blooms of beetles? "Yet when we looked at the information out there," says Turner, "there were surprisingly little data backing up that conventional wisdom."

Turner and several colleagues, including then-doctoral student Martin Simard, conducted a comprehensive study (JFSP Project No. 06-2-1-20) of interactions between bark beetles and wildfire in the Greater Yellowstone Ecosystem. Using a research framework known as a chronosequence, Simard and his team matched 20 beetle-killed lodgepole pine stands at various stages (red-needle stage, gray stage, and older beetle kills from the 1970s and '80s) with undisturbed stands of similar ages and compositions. In each stand they analyzed the dead wood closely to determine the time elapsed since the beetle attack, reconstructed the preattack structure and composition of the stand, and measured surface and canopy fuels at each stage.

"Our objective was to look at whether the probability of active crown fires would increase following beetle attack," says Simard, now on the geography faculty at Laval University in Quebec. "Active" crown fires were the team's chief concern, he explains, because these are typically the most damaging: they rise into the canopy of a forest, spread crown to crown, and end up burning huge swaths of forest. In contrast, "passive" crown fires are essentially surface fires that torch single trees and small groups of trees.

Simard measured and mapped fuels in the canopy, understory, and forest floor of the beetle-killed and undisturbed stands. Then he fed the fuels data into the fire behavior model NEXUS, which simulates surface fire spread, crown fire initiation, and crown fire spread.

In a 2011 paper published in "Ecological Monographs" (Simard et al. 2011), Simard, Turner, and their colleagues present the startling results: a wildfire that burns in a beetle-damaged stand will probably be no more intense—that is, no more likely to develop into a crown fire—than one that burns in a green stand. In fact, the fire's behavior in a red-stage stand may be less intense under intermediate weather conditions, because needles have already fallen from the dead trees, reducing canopy fuels significantly.

"We were surprised by this," Turner says. The shock of seeing a red canopy may cause people to overestimate its flammability. But the modeling results showed that, while beetles and fire are linked in complicated ways, the one does not cause the other. In fact, wrote the authors, "contrary to conventional wisdom, the interaction was a negative feedback in which the probability of active crown fire appeared to be reduced."

"Something that's perhaps not well appreciated about beetle disturbance," says Simard, "is that it's diffuse in time and space." A bark beetle outbreak starts slowly, builds up to a peak over 5 to 10 years, and subsides. A beetle-killed stand, then, may have unattacked live trees, killed-but-still-green trees, red-needle trees, and gray trees. "We say 'red-stage stands' and 'gray-stage stands' so it's easier to grasp conceptually," Simard says, "but you never have 100-percent mortality in a single year. So, by the time the stand enters the so-called red stage—that is, when the majority of trees have red needles—about half the canopy fuel is on the ground."

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Does less fuel in the canopy mean more on the surface? Yes, but not right away. "We did not observe a short-term increase in dead surface fine fuels or fuel bed depth in the gray-stage stands (3 to 5 years postoutbreak)," Simard and his colleagues noted. The increase in surface fuels comes later, in 25 or 30 years, when the dead trees have fallen.

This finding, Simard notes, doesn't square with a similar fuels chronosequence led by Michael Jenkins of Utah State University on lodgepole pine sites in northern Utah and central Idaho (JFSP Project No. 00-2-25) (Page and Jenkins 2007a, 2007b). Those

Clint Kyhl

A beetle-killed spruce-fir forest at the gray stage in Colorado's Willow Creek Pass.

researchers found short-term increases in surface fuels, even though they, like Simard's team, reported reduced canopy fuels after a beetle attack.

Simard attributes his own finding to decomposition. "The minute needles fall to the ground, they begin to rot," he says. "In general, you can have a substantial mass loss, something like 10 or 20 percent, in the first 2 years. So after 5 years, nearly half of the freshly fallen fuels may have decomposed." It's not clear why the two studies disagree; Simard points out that the sampling protocols were different and the study sites and forest conditions were not necessarily comparable.

At the stand scale, Simard's study found that wind speed and fuel moisture made more of a difference in fire behavior than structural changes from beetle damage. When the model simulated slow wind speeds and moist vegetation, fires in all stands tended to stay on the surface. When the model created hot, windy conditions, all stands eventually achieved crown fire. Hence, under low or moderate fire conditions crown fire will be constrained by the weather, and in high-severity conditions everything will burn.

The main message, says Turner, is that bark beetle infestations do not increase the risk of severe fires for those parts of the West where beetles are most troublesome. Indeed, the study predicts a reduction in most measures of fire intensity for up to 35 years after a beetle outbreak, including a reduced probability of active crown fire.

"It's important to remember that nobody is saying beetle-killed forests won't burn," Turner says. "They will burn perfectly well. The point is that they will burn no more severely than a comparable green forest." The natural pattern in this forest type is infrequent but severe wildfires. A vivid case example is the Yellowstone Park fires of 1988: "Our findings are consistent with what we saw then," Turner says. "The fires burned old forest, young forest, dense forest, sparse forest. They jumped across canyons. When fire burns like that, everything in its path will go."

Heavy Lifting

Scientists digging into the inverse relationship—whether fire injury to trees improves the beetles' colonization and reproductive success—are coming to a similar conclusion. As part of the same JFSP project, entomologists Erinn Powell and Ken Raffa and forest ecologist Phil Townsend, all of the University of Wisconsin, measured fire damage in burned lodgepole pine trees in areas with both low (endemic) and high (epidemic) mountain pine beetle populations.

Their findings suggest that, while moderately fire-injured trees may provide a refuge for beetle populations during nonepidemic periods, the trees are not likely by themselves to cause a transition into an epidemic (Powell et al., in press). "Our data show that only the moderately injured trees provide optimal conditions for beetles," Raffa says. "When trees are severely burned, that reduces the nutritional quality for the beetles and attracts a lot of competitors. And when the trees are unburned, they're pretty well able to defend themselves, at least when beetles are in the nonoutbreak phase."

Powell, Raffa, and Townsend's work affirms the larger conclusion that, while site-scale factors like fuels or burned trees may have some influence on fire patterns or beetle outbreaks, both wildfires and beetle epidemics are driven by larger-scale factors such as drought and warm weather.

Historical Beetle Outbreaks

Thomas Veblen was one of the first researchers to tackle the question of whether beetle outbreaks increase the risk of fire's occurrence, severity, and extent. Twenty years ago he and colleagues were studying areas on the Routt and White River National Forests that had been affected by a spruce beetle outbreak in the 1940s.

Comparing these with areas untouched by the beetle, the researchers saw no difference in the frequency of later fires. Veblen and his postdoctoral collaborators Dominik Kulakowski and Christof Bigler went in after the extensive 2002 wildfires in the Flat Tops Wilderness in northwestern Colorado and looked again at areas that had experienced the 1940s spruce beetle outbreak. They found that, while beetle outbreaks were not much of an influence on fire spread, previous fire history was an influence: the 2002 fires were less extensive and severe in young stands that had originated after fires in the early 20th century. "The management implication of this," Veblen says, "is that where we have a policy of prescribed natural fire [such as, for example, in wilderness areas], these natural burns buffer against future fire spread."

Veblen and his team also found that fire spread equally well in living and dead fuels. "We didn't expect this, but it's what we found. Standing dead trees were an inconsequential influence compared with weather, topography, and character of the neighboring vegetation."

In another retrospective study, Veblen and Kulakowski were surprised to find that fire spread no more extensively in a mountain-pine-beetle-killed forest in the red stage than in a comparable green forest. They did see greater fire severity (i.e., more complete vegetation mortality) in areas with many trees on the ground, but it didn't matter how the trees got there—whether they toppled in a windstorm (which these trees had, in 1997) or were felled by beetles. "Our work," Veblen says, "has shown that catastrophic fire is not an inevitable consequence of beetle kill."

Dana Hicks

Sap oozes from entry wounds made by mountain pine beetles.

To get an even longer view into the past, Andrea Brunelle with the University of Utah and Steven Munson with the USFS Forest Health Protection office analyzed ancient pollen deposits from seven alpine lakes (3,000-plus meters in elevation) in spruce-fir forests of eastern and southwestern Utah (JFSP Project No. 06-3-1-31). Their goal was to determine frequency of both fire and spruce beetle outbreaks over the past 13,000 years. They found evidence of major spruce beetle outbreaks every 600 years on average, and major fires every 350-400 years. Most of the beetle outbreaks (75 percent) were not coincident with fires within 100 years. "The reconstruction … supports the dendroecological [tree-ring] data," the researchers wrote, "which indicate that fires are not necessarily more likely following a spruce beetle outbreak."

Additional research does not challenge these findings. A 2008 survey of literature dating back to 1965 reveals no clear trends in fire-beetle or beetle-fire interactions (Simard et al. 2008). With respect to the fire-beetle relationship, the literature showed no conclusive effects of fire injury on beetle attack rates in lodgepole pine. In Douglas-fir forests, Douglas-fir beetles probably do attack fire-injured trees more readily than uninjured trees. Bark beetles endemic to Engelmann spruce and ponderosa and Jeffrey pines may also attack injured trees at higher rates, but the data are too scanty to draw conclusions. Only a few studies looked at reproductive success of beetles in fire-injured trees, and their results show no clear trends.

Doubts

Even though the Simard et al. (2011) conclusions are generally in line with previous research, some have their doubts. "I've heard mixed responses from managers," says Turner. "Some say, 'Your results make complete sense; I've seen fires drop to the ground and skunk around under the [beetle-killed] trees.' Others say, 'I've been in beetle-killed forests, and the fires are worse than they would have been [without the beetle attack].'"

Mike Battaglia, a research forester with the USFS Rocky Mountain Research Station in Fort Collins, Colorado, has expressed concern about the interpretation of the Simard et al. study. While he and some of his colleagues agree that Simard's fuels data are impressively thorough, they have quibbles about the research methods.

"I've heard mixed responses from managers…"

Specifically, Battaglia says, the fire behavior model used, NEXUS, hasn't been tested in beetle-killed forests. In addition, he believes the study didn't account for fuel moisture at a fine enough spatial resolution during the red-stage modeling. He points to research by colleagues Matt Jolly and Russ Parsons of the USFS Missoula Fire Sciences Laboratory, which shows that tree needles dry rapidly and ignite more readily as a beetle-infested stand moves through the red-needle stage. And he believes the study also inadequately addresses slope steepness (which affects the length of the flame required to set a canopy on fire) and increases in wind speed as the canopy dwindles.

Simard acknowledges that none of the available fire behavior models, including NEXUS, handle foliage moisture very well. "These models were built to work at a minimum of 70 percent fuel moisture, which is what you find in live forests," he says. "A red-stage tree will have a moisture content of 5 to 15 percent, just like a twig on the ground. But there are live trees in a beetle-killed stand, too, so the stand as a whole never has canopy moisture levels that low." For that reason, he says, it's appropriate to calculate foliage moisture at the stand level (which is how NEXUS does it), rather than at the tree level. Moreover, wind speed "was indeed considered in the modeling," Simard says; the differences posed by canopy density were derived from the team's field measurements.

The modeling predicted that, after declining during the red-needle stage, all the metrics of fire behavior—crown fraction burned, rate of spread, heat per unit area, and fireline intensity—would slowly go

Suming Jin

Ken Raffa, Bill Romme, Phil Townsend, and Monica Turner confer in a beetle-killed lodgepole pine stand.

Sky Stephens

Beetle damage on a pine branch.

back to preoutbreak levels. After 35 years, "canopy bulk density was still low, and thus only passive fires were predicted [by the model]" under intermediate conditions, according to the final project report (Tinker 2009).

Battaglia questions the "only" in that statement. "Of course: when you've lost the canopy fuels, you won't have active crown fires. But you will have passive crown fires" that can throw burning material into an adjacent stand. (Simard's team didn't look at spotting potential.) "And when all that coarse woody debris falls down, you'll have lots of fuel on the ground."

More generally, Battaglia questions the broadness of the recommendation (also expressed in Tinker 2009) that managing beetle-killed stands in order to reduce fuels "is probably not needed" in Greater Yellowstone's lodgepole pine forests. Coarse woody fuels may not contribute to fire spread, Battaglia says, but they will make a very hot fire on the site, causing managers to worry about containment, spotting, development of convection columns, and firefighter safety.

"And then a hot fire is going to cook the ground and all the regeneration," Battaglia says. "And if those trees aren't old enough to have put out cones yet, you have a problem. That's what managers are mostly worried about—not what happens during the red stage, which is a very short time, but what's going to happen in 20 or 30 years."

Forest managers in British Columbia, where the beetle epidemic has hit particularly hard, tend to agree with Battaglia. Their observations of the behavior of several big wildfires have convinced them that fires do behave differently in beetle-killed forests.

Their observations of the behavior of several big wildfires have convinced them that fires do behave differently in beetle-killed forests.

Dana Hicks, regional fire management specialist for the British Columbia Ministry of Forests, recalls the massive fires that swept through red-stage beetle-killed stands on the Vanderhoof Forest District near Prince George in 2005, 2006, and 2007. These were as intense as fires in a green forest, Hicks says, but much faster moving, "like a flashy fire that rips across the landscape, with double, if not triple, the rates of spread that you get in a green forest."

In contrast, the 2010 fires in gray-stage stands at Greer Creek in British Columbia's central interior spread about as fast as those in a green forest but were extremely intense, because there was copious regeneration and other live vegetation in the understory that burned along with the dead wood. "These were good sized, very consuming fires. We couldn't come in with an air tanker because there was so much heat and intensity."

Hicks, like Battaglia, believes fuels are more of an influence than the Simard et al. (2011) findings indicated; and, specifically, that fuel moisture makes a bigger difference. "Last year in mid-July and August," he says, "we had standing dead trees at 6 percent moisture content. For comparison, kiln-dried lumber is at 14 or 15 percent. Red-stage trees are going to have a moisture content equivalent to a stack of kiln-dried lumber—not the 100 or 120 percent [typical of a green forest]."

The few burn trials conducted in Canada have yielded no conclusive answers. Dave Schroeder of Alberta Sustainable Resource Development (wildfire operations) and Colleen Mooney of FP Innovations Wildland Fire Operations Research Group simulated a mountain pine beetle infestation by girdling jack pines at Archer Lake in northeastern Alberta in May 2007 (Schroeder and Mooney 2009). In July 2008 they burned two of the experimental stands along with control stands of green trees. In two side-by-side comparisons, crown fire developed in both the experimental stand and the control stand within seconds of each other, making it impossible to detect any significant difference in fire behavior.

Schroeder and Mooney burned these forests again in July 2009, when experimental stands were in the full red-needle stage. This time they divided the experimental and control plots into smaller parcels to achieve better replication, and they chose noncontiguous burn plots to avoid potential interactions of fires. They also chose a day with cooler, moister weather. But again the fires crowned at nearly the same moment, and rates of spread were about the same.

The size of the plots, their proximity to one another, and the differences in weather between the two burns could have obscured significant fire behavior differences, says Mooney. In addition, the thick mat of flammable reindeer lichen in both experimental and control plots—a common feature in boreal jack pine forests—fueled a surface fire of unexpected intensity.

When faced with uncertainty, scientific disagreement, and millions of dead trees, what's a manager to do?

"We're trying to do the same thing you guys are doing," Mooney says, "and that is to quantify what people are seeing out on the landscape. But so far we're not matching those reports in our experiments."

Essential Tension

When faced with uncertainty, scientific disagreement, and millions of dead trees, what's a manager to do? "From the standpoint of active crown fire or severe fire," says Turner, "I think what our results would say is, you certainly don't have to go in and cut big trees. No evidence from our work suggests that salvage logging following beetles will reduce fire risk." There may be other good reasons for taking out the wood, she says, "but if it's justified by saying we're going to reduce the risk of fire, I would say our data don't support that."

Kevin League

Tom Veblen takes a core sample from a spruce tree.

Yet some clearly have a different view. "Maybe not fire risk," argues Battaglia, "but how about fire severity? Fire growth? Fire extent? These are just as important to consider."

The collegial dispute over the Simard et al. (2011) findings illustrates the essential tension between research and practice. To invoke a familiar paradigm, science accretes knowledge bit by bit, like a coral reef. Each bit is limited, contingent, and situated in a particular time and place, and the accretion process never ends. The scientist's task is to draw larger conclusions from this slowly growing body. A scientist speaks as confidently as the data allow, but often cautions against extrapolating too freely.

The manager's task, on the other hand, is to decide to intervene (or not to intervene, which is still a decision) in the trajectory of a landscape that is already on a distinctive path, shaped by natural and human influences. The manager must judge which aspects of the science apply most strongly to his or her situation, consider the political and economic environment, evaluate the uncertainty remaining, and make the call.

That call will be enabled or constrained by prevailing policies and practices, which vary widely depending on social, economic, and political context. In most of the U.S. West, for example, aggressive salvage logging is unlikely to be the method of choice for dealing with beetle damage. There was never much of a timber industry in the Yellowstone area, and wood products in Colorado and Wyoming are greatly reduced from former days. Partly for that reason, there isn't much value in the beetle-killed wood. In addition, much of the affected forest lies in designated wilderness or roadless areas, and much of the rest is on steep slopes where logging is environmentally or economically questionable.

The key management objective in these lands is protection of human life and safety. At the lower and middle elevations, that means removing hazardous trees around campsites and along roads and trails, taking out smaller wood and (usually) piling and burning it, and working with communities to reduce fuels around homes and towns.

"Those activities are where we've been devoting most of our resources," says Steve Currey. "We've had to shut down quite a few campgrounds to remove hazardous trees before we could let people back in." The Medicine Bow-Routt National Forests have about

Monica Turner

Beetle galleries in an old log, showing that trees killed years ago still display evidence of beetle attack.

200 campgrounds, and after 3 or 4 years of hard work, "we're just about done."

Currey and his staff are also working with communities to reduce fuels around homes and towns—an ongoing effort that's been made more urgent, at least in the public mind, by the beetle epidemic. There is a lot of expensive real estate near ski towns. "People have built homes in pure lodgepole pine forests," says Veblen. "Even many years before the outbreak, experts were saying, 'This is a disaster waiting to happen.' So maybe we should view this outbreak as a teachable moment."

At higher elevations, the most effective strategy is probably to do nothing beyond clearing the most used trails. The acreage of spruce-fir forest killed by spruce beetles in western Colorado doubled to 208,000 acres between 2009 and 2010, says Veblen, and it continues to grow rapidly, especially in the remote San Juan Mountains. Given that spruce-fir forest covers three times as much area as lodgepole pine, the spruce beetle could end up affecting more acres of Colorado forest than the mountain pine beetle, he says. "Yet the public doesn't know much about these areas, because they're in the high back country," where natural fires, if allowed to burn, could buffer against future major blazes in both beetle-killed and undisturbed areas.

Long-Term Risk?

The next task, say some managers, is to address any long-term fire risk that bark beetles may have brought into the landscape. Many believe that investing in fuel management now—whether through mechanical removal, salvage logging, prescribed or natural fire, or some combination of techniques—will pay off later in more heterogeneous and less fire-prone forests.

"We're looking out several decades at what the future forest is going to be," says Currey. "With 1.2 million acres of dead pine, if we do nothing, we're going to end up with one age class again, and that's not a good place to be."

The JFSP is supporting research into methods of reducing fuels in beetle-killed stands without unduly affecting soil, water, and regeneration. For example, Rhoades and Battaglia are in the midst of a study (JFSP Project No. 09-1-06-16) of the effectiveness of current fuel treatment methods, including salvage logging, in forests with severe bark-beetle impacts. "We're looking at the implications of different management practices," Rhoades says, "not just cut or don't cut, but how you harvest and how you leave the slash, and what that means for regeneration of the forest, changes in fuel loads, and changes in fire behavior over time."

Previous studies led by Rhoades, Battaglia, and others show that the forest is regenerating itself well without fuel treatments, but that logged stands are more likely to come back to lodgepole pine instead of some other species (Collins et al. 2010, 2011). "Most of our [study] stands will regenerate into full forests in about 100 years," says Rhoades, "but the unsalvaged stands are more likely to be dominated by subalpine fir. That's interesting, not only because fir is not a favored commercial species, but because fir provides a more efficient ladder fuel for crown fire." However, he says, "the big take-away message is that there's going to be a forest coming back no matter what you do."

Rhoades and Battaglia are doing additional work on some of the same study sites to test the longevity of fuel treatments. One question they want to answer is whether keeping logging slash onsite might slow understory regeneration and perhaps reduce fire risk for a longer period.

As for the effects of salvage on fuels, says Battaglia, the salvaged stands initially have more surface fuels because of the logging slash. However, growth modeling suggests that will change: "After about 20 years, your surface fuels in the unharvested stands are two or three times greater" than in the harvested, lodgepole-dominated areas.

"The other interesting thing we're seeing," Battaglia says, "is a nice bump in aspen regeneration in both types of stands, but a greater density in the harvested stands." This is good news in terms of fire behavior, "because aspen has historically served as a fuel break—it's hard to get it to burn. And people and wildlife like it."

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Studying the effects of salvage logging of beetle-killed lodgepole pine on the Bridger-Teton National Forest, Turner's student Jake Griffin and his colleagues found that it reduced the total density of advance regeneration—young trees that were spared the beetle attack—but that lodgepole saplings did not decline and enough remained to ensure the stand would grow back to lodgepole pine. "That's a good finding," Turner says, "because other studies have shown salvage harvest to have a strong negative effect on advance regeneration." The team noted significant differences in fuel patterns: salvaged stands had less canopy fuel but more surface fuel in the form of logging slash.

A related study, also led by Griffin, showed that beetle outbreaks in lodgepole pine did not affect soil nitrogen availability as much as was expected (Griffin et al. 2011). Stand-replacing disturbances like fire can put excess nitrates into the soil that leach into neighboring streams, impairing water quality and draining the site of plant-nourishing nitrogen. Griffin and colleagues found that trees and other plants that survive the beetle attack take up the released nitrogen, which stimulates their growth and may help to prevent leaching by keeping nutrients on the site.

Other case studies examining fuel treatments are being conducted on other national forests. One study on the Medicine Bow-Routt called for a 70,000-acre thinning in an attempt to halt the beetles' spread. "That didn't work," says hydrologist Liz Schnackenberg, who is part of that team. "The beetles have come and gone, and we are left with dead forests of lodgepole." The trial is now in its second phase, which calls for salvage logging, but it is too early to say whether the treatments have reduced the risk of severe fire.

Managers on that forest are also doing experimental prescribed burns. "We hope to do more of these in the future," says Currey. "We want to provide more of a mosaic of species and age classes, and we want to do it on our terms, not on Mother Nature's terms." Prescribed fire is cheaper than taking fuels out with machines, says Currey, but environmental concerns, chiefly smoke hazard, can make burning administratively difficult.

Schnackenberg would like to see much more operational burning on the Medicine Bow-Routt. "My opinion as a hydrologist is, I would rather see all that dead stuff burn right now. It's standing, and if we wait for it to fall there may be places where it will burn a little hot, and you'll get hydrophobic soils and erosion. And if you have heavy fuel loads on the ground in 15 years and a fire comes, what happens to the hydrology then?"

Wild Card

The biggest wild card in the fire-beetle relationship is climate. "A warming climate," says Turner, "is almost certainly why we're seeing such a big infestation now." Warmer temperatures bring drought, which stresses trees and makes them more susceptible to beetles, and warmer winters enable more beetle larvae to survive and breed.

Turner is co-investigator on a JFSP-supported study published in July 2011 that suggests climate warming could completely transform fire regimes in the Greater Yellowstone Ecosystem over the coming century, shifting now-forested areas into sparse woodlands or grasslands (JFSP Project No. 09-3-01-47; Westerling et al. 2011). The paper's lead author is Anthony Westerling, who also led a noted 2006 study linking warming temperatures and earlier springs in the Rockies with increased wildfire activity.

The researchers in the current study identified statistical relationships between recent climate data and large fires in the northern Rockies. Then they ran their data through three global climate models to predict how many fires would start and how much area would burn yearly between now and 2099.

The modeling predicted more extreme fire seasons and more area burned annually, even in low fire years, which would become less common. "There is a real likelihood of Yellowstone's forests being converted to nonforest vegetation during the mid-21st century," the researchers found, "because reduced fire intervals would likely preclude postfire tree regeneration."

Conclusion

It is pretty well accepted that once beetle outbreaks cross certain thresholds, they become too big to stop. Very small-scale remedies may be effective—for example, installing pheromone traps to attract beetles away from vulnerable trees. But a landscapewide infestation, like a big hot fire, is an irresistible force of nature. "It's just going to run its course," says Currey. "So that leaves us with how to mitigate the effects."

That is a big "how." And, as with most knotty management problems, the science can guide, but it cannot direct. Wildfires and bark beetles don't lend themselves to controlled studies, and the findings don't usually point to neat, out-of-the-box solutions.

More than that, even the most undisputed ecological knowledge is inflected by political, economic, and social considerations. A set of findings like Simard's, however accurate and useful in theory, may or may not govern management response at the level of stand, forest, or watershed. Any prescription will also rely on other research and on-the-ground experience, and any action will hinge on local constraints and opportunities.

Further Research Needed

- More experimental burning. "With modeling, it's not a real fire; with retrospective studies, it's hard to know exactly what burned. With experimental fires, you can measure and know exactly what's happening." (Martin Simard)
- Improved fire behavior models. "The weakest part of fire behavior models is the way foliage moisture is handled. There is work being done that will eventually fit into fuel models and make them better. Also, U.S. models are mostly designed for low-intensity, high-frequency fire regimes like ponderosa pine. They are not adequate for boreal and subalpine forest." (Martin Simard)
- Improved understanding of how fire and beetle outbreaks change the landscape. "What's the relative importance of stand structure, topography, soil characteristics, landscape context, and beetle pressure in different forest types under beetle attack?" (Monica Turner)
- Long-term hydrological research to determine lingering ecological effects of beetles and fire, and also of human disturbances like salvage logging. "The consequences of management have great longevity. What we do now will reverberate in the system for a century. In the name of managing for fuels, fire risk, and human safety, it's important not to do long-term damage to soils and watersheds." (Chuck Rhoades)
- Better understanding of beetle interactions with naive hosts in high-elevation ecosystems. "How do the defenses of trees compare with those of historical hosts, and what mechanisms are most important? Are there sources of genetic resistance among separated populations?" (Ken Raffa)

The first thing managers should do, say scientists, is pay attention to the basic ecology of an affected forest system (Romme et al. 2006). After that, it's important to avoid a crisis mentality and to be clear about one's mission. "If your objective is to have sustained extraction of wood products," says Raffa, "then that will trigger a certain set of tactics. If, on the other hand, you want to manage for biodiversity, then you should incorporate the ways in which bark beetles can contribute to biodiversity."

For most forest managers in the U.S. Intermountain West, the favored pathway will lie somewhere between those poles. To make the best choices, they will need to negotiate the ecological, economic, and social realities that characterize the working environment of a 21st century forester.

"Most managers understand that climate is the strongest driver," Turner says. "But they may be fearful of severe fires, and they may be fearful of what the public or lawmakers would say if a fire gets out of control. They want to be able to say, 'We did everything we could.'"

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JFSP *Fire Science Digest*
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Credits

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