Do trees that are killed by bark beetles trigger more severe wildfires than those that are unaffected?

Processed-based fire models: new tools for an era of novel conditions

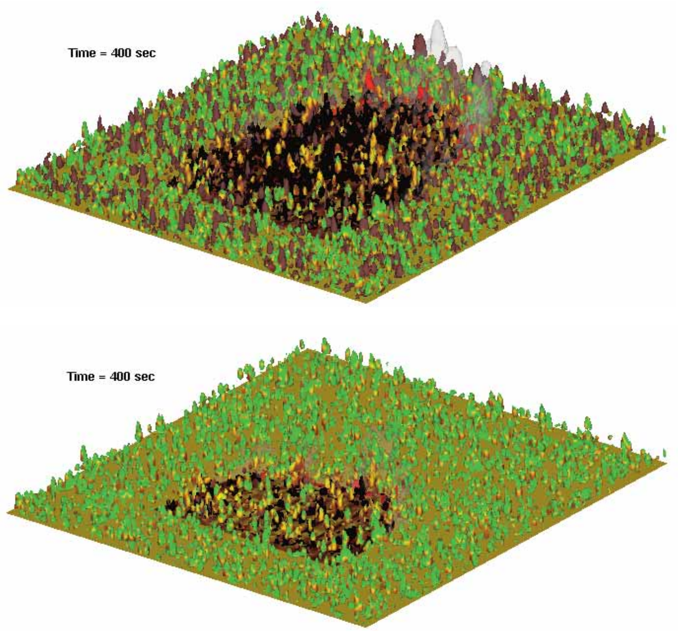
The first few years of the 21st century brought a series of unprecedented natural disturbances to the southwestern U.S. A severe drought, later tagged as a "global change type drought," triggered the mortality of 1,000 of native trees. For some species, such as the ponderosa pine, the drought was especially lethal due to high tree densities which were the outcome, in part, of the impacts of past management practices. Already crowded, and competing for water, the drought further weakened the pine trees, making them more susceptible to mortality due to several species of bark beetles that feed on the cambium and in doing so kill them. Entire hillsides were covered with dead and dying trees as the result of the bark beetles, raising concerns that forests would be susceptible to severe wildfires. There was already evidence that fire seasons were starting earlier and lasting longer, and both Arizona and New Mexico experienced their largest fires in recorded history between 2000 and 2015. This unprecedented series of events highlighted the need for better tools to understand and predict fire behaviour under novel conditions.

In the past, wildland fire science had relied heavily on empirical models based on correlations between fire behaviour attributes (such as fire spread) and fuel parameters (e.g., the amount of fuel) from laboratory or field observations. These empirical models form the basis for several fire prediction platforms that are easy to use in the field. However, as interest grows in the ecological effects of fire in conditions beyond the limits of current empirical models such as occurred in the Southwest recently, new tools are being developed that represent the processes that drive how fires ignite, spread, and develop. For example, interests in incorporating spatial heterogeneity in fuels, or the effects of dead fuel or fluctuating winds into fire behaviour predictions requires new tools. In recent decades, process-based simulation modelling has developed due to advances in computational capacity and computational fluid dynamics. These process-based models are not merely more complex empirical

Introducing bark beetles

Ponderosa pine is a widespread species in North America that is found from Canada to Mexico and throughout the west of the U.S. Ponderosa pine is one of several species of pines to experience extensive and unprecedented mortality in recent decades due to a combination of drought and forest conditions that favour bark beetle epidemics. Early in the 21st century, a global change-type drought triggered extensive bark beetle-caused mortality in the southwestern U.S. The bark beetles responsible for the tree mortality in our study in Arizona included a suite of species.

Early in the beetle outbreak, two species of Ips beetles were responsible for much of the tree mortality. However, later in the outbreak, several species of pine beetles in the genus Dendroctonus also played an important role in killing trees. Both genera of bark beetles attack trees by boring through the bark en masse and laying their eggs in the cambium (inner bark). When the eggs hatch, the larvae feed on the cambium, and after completing their development, the adults bore out of the tree and begin another generation. In addition to the tree being girdled by boring and feeding, the bark beetles also introduce a blue stain fungus that blocks water flow in the tree and aides in killing of the tree. In trees killed by bark beetles, the pine needles fade, turning from green to a brownish-red colour in the first year, and then fall to the ground and the needleless trees become grey. We used a process-based fire model, FIRETEC, to explore how fire severity changes with different levels of mortality during three temporal stages ("green," "red," and "grey") under three different wind speeds. These simulations captured these early stages following bark beetle-induced tree mortality, before the dead trees fell to the ground.



We conducted a virtual experiment using a process-based fire model, FIRETEC, to detangle the mechanisms thought to control fire severity in forests attacked by bark beetles. This pair of simulations, stopped at 400 seconds after ignition in a low wind speed scenario show that the fire burns more severely in the "red" stage when dead needles remain on branches (top) than in the "grey" stage when the dead needles have fallen to the ground (bottom)

models, but rather are designed to mimic the mechanistic behaviour of fire by representing the controlling processes and their interactions with each other and the environment.

The development of process-based fire models has created opportunities for researchers to capture complexity in the types of questions they can ask as well as the way that they can address their questions—from understanding basic fire phenomenology to applied work that addresses managers' questions about how forest treatments might alter fire behaviour. These models also provide a new type of platform in which to study wildland fire behaviour. That is, they can be used to conduct experiments that simply could not be conducted in the real world because they are impossible, too costly, or too risky. We highlight below the application of a process-based fire model for conducting a virtual experiment to explore the interaction of two natural disturbances, bark beetle-caused mortality and fire.

Fires following bark beetles

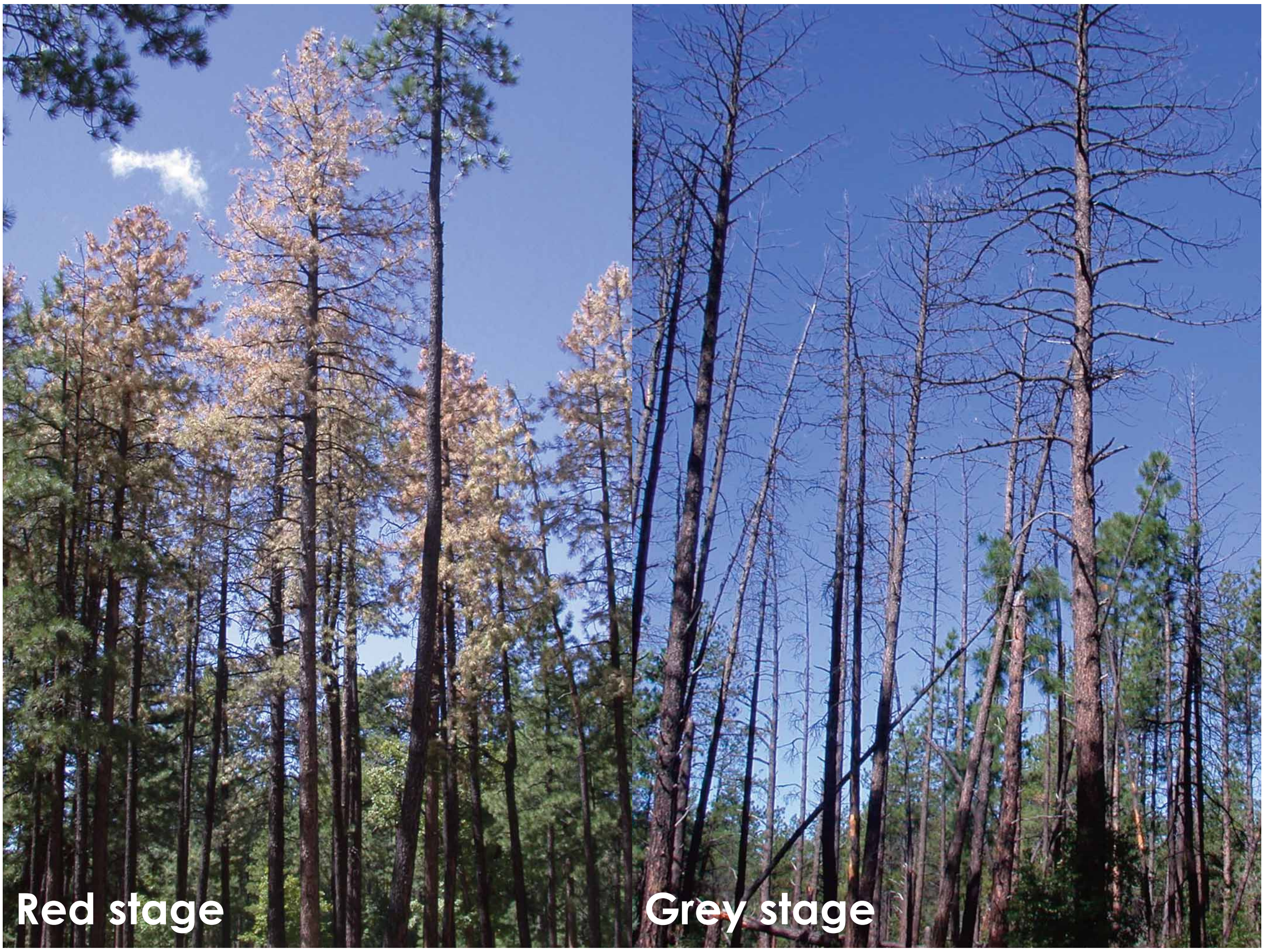
Let's return to the question of whether dead and dying trees killed by bark beetles might trigger more severe wildfires than might burn in a green forest unimpacted by bark beetles. A decade or more of studies and countless media reports have reported conflicting assessments as to whether bark beetle-caused tree mortality leads to more severe wildfires. It turns out that the severity of a fire following bark beetle-caused mortality may depend upon several factors, including the forest type, time since the tree mortality, amount of mortality, and weather conditions during the fire.

Yet, studying how a fire might behave following bark beetle-induced tree mortality is fraught with difficulties. In natural forests, it is virtually impossible to find identical plots with the same level and recency of mortality that burned under the same weather conditions. Moreover, the currently available empirical models cannot account for spatial heterogeneity in fuels, fuel moisture of dead pine needles, varying and fluctuating winds, nor the interactions between the fire, fuels, and wind. This is where simulations based on field data using process-based fire behaviour models can provide valuable insights.

Our recent paper (Sieg et al. 2017) demonstrates the use of a three-dimensional process-based model, HIGRAD/FIRETEC, to simulate fire behaviour in fuel beds representative of field plots in ponderosa pine forests in Arizona, USA. The process first involved building a virtual forest to input into the model. Very detailed, spatially explicit data is needed to build this virtual forest. The goal is to characterise the fuel biomass in each ~2- by 2-m cube. This virtual forest was based on field data we collected in 60 field plots where we took detailed measurements. Creating a spatially explicit input file allowed us to both represent the natural variability inherent in forests and to have identical starting conditions for our virtual experiment. In addition to controlling for initial forest conditions, we then altered other factors that are known or thought to contribute to varying fire severity following bark beetle-induced tree mortality. Specifically, we were interested in how fire severity, measured by how much live canopy fuel survived the fire, varied by the stage and amount of mortality under varying wind conditions.

Virtual burns: searching for reasons behind fire severity

We modelled the early stages of bark beetle mortality, including the "red" stage (in the first year or so after mortality, when the needles turn red but stay on the tree), and the "grey" stage (when the needles fall to the ground, but before the trees fall over). To simulate different levels of bark beetle-caused mortality, we randomly selected to "kill" 20%, 58%, or all the ponderosa pine trees, which represented the range and mean of mortality we observed in the field. For "red" stage simulations, trees retained their entire canopy biomass, but we reduced canopy fuel moisture to 15% (based on published data). For "grey" simulations, dead needles were removed from the tree biomass and added to the surface fuels. Since we were interested in how fire severity differed relative to live forests, our simulations all included a comparison to fires burning in no mortality settings ("green"). We then virtually burned each of these scenarios under three wind speeds. Implementing an experiment like this in the real world would be virtually impossible.



When bark beetles kill ponderosa pine trees, the needles first turn brownish-red in what is referred to as the "red" stage. Simulations indicate that fires generally burn more severely during the brief "red" stage than in the "grey" stage when needles fall to the ground

These virtual burns allowed us to disentangle the various factors that influence fire severity following bark beetle-induced tree mortality. We found that the stage of the bark beetle mortality was a key driver of fire severity. Our virtual burns revealed that fires burned more severely during the "red" stage compared to fires that burned in green forest conditions. However, the influence of mortality in the "red" stage on fire severity was most profound under low wind conditions, and almost non-existent under high wind conditions. For example, live canopy loss following fires burning under low wind speeds in the "red" stage with 58% pine mortality was 53% higher than fires burning in green forests. In contrast, for fires burning under high wind speeds, the fire severity in the red stage was nearly identical to severity in the green stage.

Yet, unlike "red" stage results, the transition to the "grey" stage revealed a general dampening of fire severity across most levels of mortality and wind speeds compared to post-fire severity in the green stage. That is, our simulations during the "grey" phase suggested that bark beetle-induced mortality decreased fire severity by eight to 34% compared to fires in green stands. We attributed this general dampening of fire severity in the "grey" stage to the loss of canopy biomass when the needles fell to the ground. However, the simulations revealed an exception to the general dampening effect of bark beetle-induced mortality in the "grey" stage. For fires burning under low wind speeds in forests with only 20% mortality in the "grey" stage, fires may burn more severely than green stage fires. We attributed these unexpected results to both the decline in canopy fuels, which allows greater wind penetration that invigorates the fire, and to the slight increase in surface fuels, which enhanced the surface fire. Collectively, these simulation results suggest that in the initial stages of mortality following a bark beetle attack, especially under low wind speeds, fires may burn more severely when red needles are present, but then usually burn less severely than fires in live forests as the dead needles fall to the ground.

The design of our experiment that controlled for initial conditions and incorporated a range of three factors thought to control fire severity following bark beetle mortality helps explain seemingly contrasting results among previous studies. Our work demonstrates the complex influences of bark beetle-caused mortality on the severity of

A cut-away of the bark of a ponderosa pine tree revealing the egg and larval feeding galleries in the inner bark made by the Arizona five spine dips bark beetle

subsequent fires. Depending on the temporal stage of the bark beetle-caused mortality and attack severity, as well as fire weather (in this case wind), bark beetle-caused mortality may or may not result in more severe fires. Notably, wind speed was a key factor, and is one that deserves more attention in future studies. Process-based models can play a particularly important role in advancing ecological knowledge, in part, because they allow users to evaluate the potential mechanisms and interactions driving fire dynamics and effects from a unique perspective not often available through on-the-ground studies.

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