

## Use of prescribed burning for restoration and maintenance of ecological conditions: Predicting and managing fire injury and tree mortality

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**Abstract:** Throughout Earth's history fire has been a major disturbance factor in many terrestrial ecosystems. Fire is man's first tool. It was used for a host of cultural purposes to modify stand structure and species composition as well as landscape pattern and process. Changes in climate and land use are leading to changes in vegetation and the frequency and severity of modern fire disturbances. As a major determinant of historic vegetation structure and species composition it is appropriate to consider using fire as a restoration tool. The ecologically principaled, safe, effective use of fire in restoration requires integration across diverse disciplines from the physics and chemistry of combustion and heat transfer to biology and ecology. This paper is a primer on recent research on the effects of fire on conifers with emphasis on Europe and western North America and is intended to foster dialog and additional research on the role and use of fire in restoration.

**Keywords:** forests, conifers, prescribed fire, fire effects, fuel treatment, restoration

### Introduction

To varying degrees most of the world's ecosystems have been modified by active, intentional management often involving fire (Ruddiman, 2003; Crutzen and Goldammer 1993; Pyne 1995). It is widely accepted that man's first tool, fire, has been used throughout the ages to improve hunting, grazing, and pasture management and to clear land for agriculture and defenses. The role and use of fire and ecological considerations for restoration are addressed in numerous texts (Trabaud 1987; Crutzen and Goldammer 1993; Whelen 1995; Bond and van Wilgen 1996; Johnson et al. 2003; Thomas and McAlpine 2010), particularly circumpolar boreal forests (Wein and MacLean 1983; Goldammer and Furyaev 1996); tropical forests (Cochrane 2009); wetlands (Ceruleon and Engstrom 1995); and temperate forests and semi-arid woodlands in Australia (Gill et al. 1981), Europe (Monteil and Kraus 2010; Silva et al. 2010), North America (Agee 1993; Sugihara et al. 20060; South Africa (van Wilgen et al. 1997); and the Mediterranean Basin (Trabaud and Prodon 1993).

Many species evolved in such close association with fire that they possess attributes specialized for exploiting the post-fire environment either through survival (resistance) or rapid regeneration (Gill et al. 1981; Wein and MacLean 1983; Goldammer and Furyaev 1996; Sugihara et al. 2006; Paula et al. 2009). Many landscapes contain a mosaic of patches critical to wildlife habitat requirements. Likewise many plant communities and landscapes hold great cultural significance. These have changed substantially in recent times due to urban migration, loss of traditional practices, and changed management philosophy. Changes in land management have modified species composition, stand structure, fuel dynamics and fire potential, often with undesirable social consequences and increased interest in restoration.

Throughout civilization man has altered the role and use of fire to meet the perceived needs of the time. For example, fire was routinely used to clear land for agriculture and to restore and maintain pasture forage. When populations declined due to wars and plagues, or migrated to urban or other areas, natural succession led to invasion of old fields and woody plant encroachment into grasslands (Ruddiman 2003). If fire was the process that created the desired conditions then fire is the process that needs to be restored. Other reasons to consider fire use in a restoration context include creating buffers to minimize the risk of wildfires entering or leaving a bioconservation or restoration project area. In each case it is necessary to predict fire behavior and subsequent responses at the individual, species, community, and landscape levels. Successful use of fire requires the integration of fire behavior and fire effects knowledge into the planning, implementation, and monitoring of restoration projects. Managers need guidelines on how to safely and effectively apply fire to meet desired restoration goals. These guidelines need to be based on knowledge of the interactions between fuel consumption, fire behavior and critical tree morphological characteristics that confer resistance to thermal injury. Likewise knowledge is needed on how injuries affect survival and growth.

The goal of our research is to understand the biophysical processes associated with safe effective use of fire as a restoration management tool. To do so requires the interdisciplinary integration of the dynamic fire environment with the combustion and heat transfer mechanisms that couple fire behavior to tissue injury and then integrate that knowledge with plant vital attributes and successional community dynamics. The dynamic fire environment is itself a complex interaction of spatial and temporal fuel/vegetation and weather/climate, dynamics with terrain influences (Ryan 2002). The objective of this paper is to highlight some of the things we have learned from observing and modeling wildland fires and post-fire responses.

## Synthesis

Restoration of fire in fire dependent forest and treatment of hazardous fuels in and around communities and within municipal watersheds requires careful consideration of the effects of fire on trees. Fire effects vary both with fire behavior and species-age related morphological characteristics (Table 1). Likewise trees vary in their response to fire injury depending on the type of tissue injured and the degree of injury (fig. 1). Trees consist of three highly integrated organs: crown, roots, and stem or bole. These organs have differing physiological functions and morphological properties that are important considerations in prescribed burning. Fires burning in various vegetative fuel complexes and under differing weather conditions have energy release characteristics and associated temperature histories and effects (Ryan 2002; Hood et al. 2007; Fernandes 2010).

Empirical observation and physiological process modeling (Ryan et al. 1993a,b; Ryan 1990, 1998; Fernandes and Rigolot 2007; Hood et al. 2007; Catry et al. 2010; Fernandes 2010) suggest that, in the absence of other injuries, light defoliation (<30%) causes minor growth losses and little mortality. Moderate defoliation (30-60%) is associated with significant short-term growth losses and increased susceptibility of insect attack and mortality. In most pines insect attack and mortality increases rapidly as defoliation approaches 100 percent. Three factors not illustrated in figure 1 modify the outcome: First, tree vigor affects resilience to tissue loss. The relationship between the proportion of crown defoliated and probability of mortality approaches linearity for low vigor trees and the fourth power in high vigor trees. Second, bud kill is more important to survival than mere crown scorch (defoliation). Trees with large dormant buds are more resistant to injury. Third, some species in fire prone environments exhibit prodigious sprouting from epicormic buds even after crown fires. Such trees are the most resistant and resilient.

The major factor affecting stem injury is the dynamic interaction between the fire's energy release and the tree's resistance to heating. Resistance to heating is principally determined by the thickness of the dead outer bark which varies by species, diameter, and site. Resistance increases with the square of bark thickness. The difference in duration necessary to kill tissues

Table 1. Tissue injury results from the interaction of critical fire environment variables interact with species and age/size morphological characteristics (adapted from Ryan 1998).

Physio-morphological Unit	Critical Fire Environment Variables	Factors Affecting Response
<b>Crown</b>	<p><u>Fuels:</u></p> <ul style="list-style-type: none"> <li>•mass &amp; depth of fine (&lt;5mm) fuels</li> </ul> <p><u>Weather:</u></p> <ul style="list-style-type: none"> <li>•wind, temp. (°C), %RH</li> <li>•short-term(≤3 days) drying</li> </ul> <p><u>Fire Behavior:</u></p> <ul style="list-style-type: none"> <li>•peak surface fire intensity</li> <li>•head-fire &gt; backing-fire</li> <li>•convection &gt; radiation</li> </ul>	<ul style="list-style-type: none"> <li>•foliage kill vs. bud kill</li> <li>•crown vigor</li> <li>•(color, length, density)</li> <li>•bud size (mm)</li> <li>•phenology (active vs. bud set)</li> <li>•epicormic buds vs. none</li> </ul>
<b>Stem</b>	<p><u>Fuels:</u></p> <ul style="list-style-type: none"> <li>•mass &amp; depth of coarse (≤7cm) fuels</li> </ul> <p><u>Weather:</u></p> <ul style="list-style-type: none"> <li>•mid-term(2-20 days) dryness</li> </ul> <p><u>Fire Behavior:</u></p> <ul style="list-style-type: none"> <li>•surface fire duration</li> <li>•head-fire ≥ backing-fire</li> <li>•conduction, radiation &amp; convection</li> </ul>	<ul style="list-style-type: none"> <li>•circumference killed</li> <li>•height killed</li> <li>•bark moisture (%)</li> <li>•bark thickness (cm)</li> </ul>
<b>Root Crown/Roots</b>	<p><u>Fuels:</u></p> <ul style="list-style-type: none"> <li>•duff depth (cm)</li> <li>•duff moisture (%)</li> </ul> <p><u>Weather:</u></p> <ul style="list-style-type: none"> <li>•long-term(&gt; 30 days) dryness</li> </ul> <p><u>Fire Behavior:</u></p> <ul style="list-style-type: none"> <li>•ground-fire duration (hr)</li> <li>•conduction</li> </ul>	<ul style="list-style-type: none"> <li>•root-crown bark thickness (cm)</li> <li>•rooting depth</li> </ul>

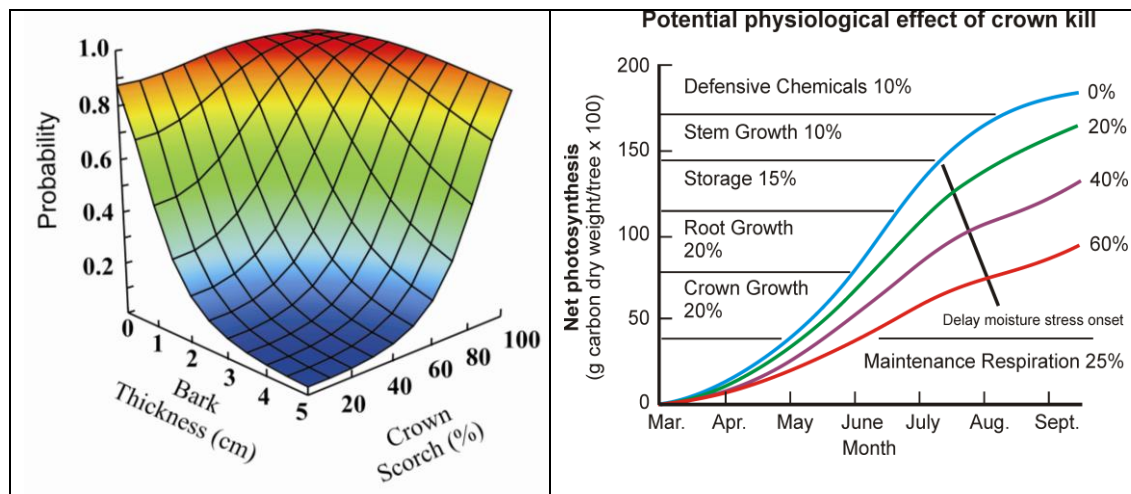


Figure 1. Tree mortality varies with bark thickness and crown injury (l). Decreases in net photosynthesis and carbon pools delay in the onset of daytime moisture stress are among potential physiological effects of crown kill for a temperate forest conifer. (adapted from Ryan 1989.)

only varies about  $\pm 50$  percent between a mild surface fire and the most intense crown fire. Because of limited variability in the burning rate of surface fuels there is a low probability of death to cambium of bark thicker than about 2 cm. Influence of cambium injury to mortality is not well known, but is strongly non-linear and on the order of the 3<sup>rd</sup> power of proportion of circumference killed for species studied. The influence root injury is poorly understood because the difficulty of quantifying the spatial distribution of roots and their temporal dynamics. The dominant observable effect is basal girdling of the root crown due to the burnout of forest floor humus. Deep duff consumption is

associated with deep soil heating and increased basal girdling. While duff consumption is predictable and is known to increase mortality, its actual influence has not been quantified.

## Conclusions

Fire ecologists have accumulated a considerable body of knowledge on fuels, fire behavior, and tree resistance/response relationships. The interdisciplinary integration fire science and physiological ecology provides a foundation for the design and implementation of restoration projects. Fire restoration projects should strive for strong partnership with scientists and employ adaptive management principles to improve understanding and future restoration outcomes.

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