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To cite this version:

Kevin C. Ryan, Eric Rigolot, Francisco C. Rego, Herminio Botelho, José A. Vega, et al.. Prescribed fire applications in forest and woodlands: integration of models and field studies to guide fire use. 3. Fire behavior and fuels conference, Oct 2010, Spokane, United States. hal-02757820

HAL Id: hal-02757820
https://hal.inrae.fr/hal-02757820v1

Submitted on 4 Jun 2020

Proceedings of 3rd Fire Behavior and Fuels Conference
October 25-29, 2010, Spokane, Washington, USA

Edited by
Dale D. Wade
Mikel L. Robinson

Published by the
International Association of Wildland Fire
3416 Primm Lane
Birmingham, Alabama, 35216 USA

2010

Proceedings of 3rd Fire Behavior and Fuels Conference, October 25-29, 2010, Spokane, Washington, USA
Published by the International Association of Wildland Fire, Birmingham, Alabama, USA

Prescribed fire applications in Forest and Woodlands: Integration of models and field studies to guide fire use

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Abstract

Globally prescribed burning is widely used for agro-forestry, restoration, and conservation to modify species composition and stand structure. Commonly stated goals of prescribed burns include to reduce hazardous fuels, improve species' habitat, reduce the potential for severe fires in the wildland urban interface or protect municipal watersheds. Treatments may focus primarily on modifying conditions at the stand level or to change the mix of mosaic patches at the landscape level. Given the wide range of vegetation/fuel types, management objectives, and human resources it is not possible to conduct field studies to acquire the empirical data to guide fire use in the full range of applications. The integration of empirically-based models with biophysical process models holds promise for being able to extend our knowledge, develop interim guidelines for prescribed fire applications in novel situations, identify knowledge gaps, and set future research priorities. Based on their experience in forests from North America and Eurasia, the authors have begun to synthesize the fire effects literature and identify common data sets for comparative analysis. This paper reports preliminary results of this effort.

Additional keywords: conifers, fire effects, fuel treatment, restoration

Introduction

Vegetation/fuels, climate, and disturbance processes, particularly fire, are dynamically coupled. People, through their impacts on vegetation/fuels, climate and disturbances, as well as their responses to disturbances, are an integral part of the global system. Twenty-first century land management requires a higher level of interdisciplinary integration of the physical, biological, and social sciences than ever before. Vegetation/fuel management activities can no longer be based on single- or narrowly-focused resource outcomes. It is now necessary to integrate multiple resource and societal benefits including species viability, clean air, clean water, public safety, and sustainable human livelihood. Activities need to integrate across increasingly large spatial and temporal domains. This requires that managers and policy makers have ready access to the best available science and decision support tools to guide their planning and implementation. Because management is today more complex than ever before, it is imperative that it be based on sound foundational science.

Fire is a natural ecosystem process and many vegetation types have recognized fire regimes that describe the frequency, timing, and severity of the fires that created the dominant stand conditions, whether these resulted from natural ignitions or a pattern of repeated human ignitions. 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). For woody vegetation, adaptations include specialized morphological characteristics such as thick bark, high open crown, large buds, and epicormic buds that are adapted to reoccurring fire (Hare 1961; Ryan 1982; Peterson and Ryan 1986; Ryan 1990). Controlled burning under prescribed conditions is commonly used to alter species composition, reduce competition, enhance wildlife habitat, improve forage, and reduce the risk of catastrophic wildfires. Likewise mechanical treatments are often applied with the intent of reducing either the likelihood or severity of future disturbances. Designing treatments that effectively increase the residual forest's or woodland's resilience to future fires requires robust models that integrate fire behavior with tree injury and postfire survival and growth (Butler *et al.* 2010; Dickinson and Ryan 2010; deGroot 2010).

The authors have begun a review and synthesis of existing fire injury-response science. This synthesis and review builds on the authors' years of experience in Eurasian and North American fire ecology. The purpose of this activity is to develop interim models and guidelines for fuels treatment and restoration activities and to identify research needs. The purpose of this paper is to review basic principles.

Synthesis

Fuels treatment and restoration projects are developed either to modify the potential impact of fire on individual sites or fire's effects at the larger landscape scale. Whether a project is classified as a fuel treatment or restoration depends primarily on the project's objective(s). Similar scientific information and logic need to be applied in either case. Landscapes are made up of sites, each site having its own particular species composition, stand structure, disturbance history, and fire regime. Sites have unique histories resulting from past grazing, hunting, harvesting (fuel, fodder, timber), tilling-farming, and settlement-abandonment. Each sites has a specific rate of change which reflects the underlying site properties (soils, nutrition, precipitation, insolation), specific responses to disturbance, specific response to removal of disturbance, and unique fire relationships. Likewise sites and landscapes have strong social relationships owing to the history of land use and local attitudes towards fire (Daniel *et al.* 2007; Montiel and Kraus 2010; Silva *et al.* 2010). All of these factors should be considered when developing fuel treatment and restoration projects.

Fuel treatment and site restoration employ mechanical manipulation/removal, chemicals, controlled grazing, prescribed burning, or combinations thereof. Where the desired historic stand conditions were strongly influenced by repeated fires, whether by natural or human ignition, prescribed fire is often the most likely process to restore the desired conditions. In addition to being the most ecologically sound treatment, prescribed fire is often the most cost effective means of fuel treatment and restoration. However, excessive fuel build-up can lead to excessively severe fire effects which may compromise treatment goals (Rego, 1991; Rego *et al*. 1993; Vega *et al*. 1994; Botleho and Rigolot 2000). Thus mechanical pretreatment or multiple light burns may be necessary to reduce fuels prior to resuming the desired burning regime, or in some cases to enhance fuels to achieve objectives. In order to achieve management objectives it is necessary to develop and implement a burning prescription tailored to the specific site/stand. Prescriptions for burning define the set of fuel and weather conditions and the ignition pattern that will yield the desired effects. The final outcome of a burn treatment is influenced by pre- and post-burn conditions in addition to the actual fire (Fig. 1). All these factors should be considered in an iterative problem resolution framework. If the current fire environment, principally vegetation/fuels precludes achieving resource objectives during probable fire weather then one or more non-fire treatments will be needed before intentional fire can be introduced. . The same suite of factors needs to be considered when formulating the burning prescription.

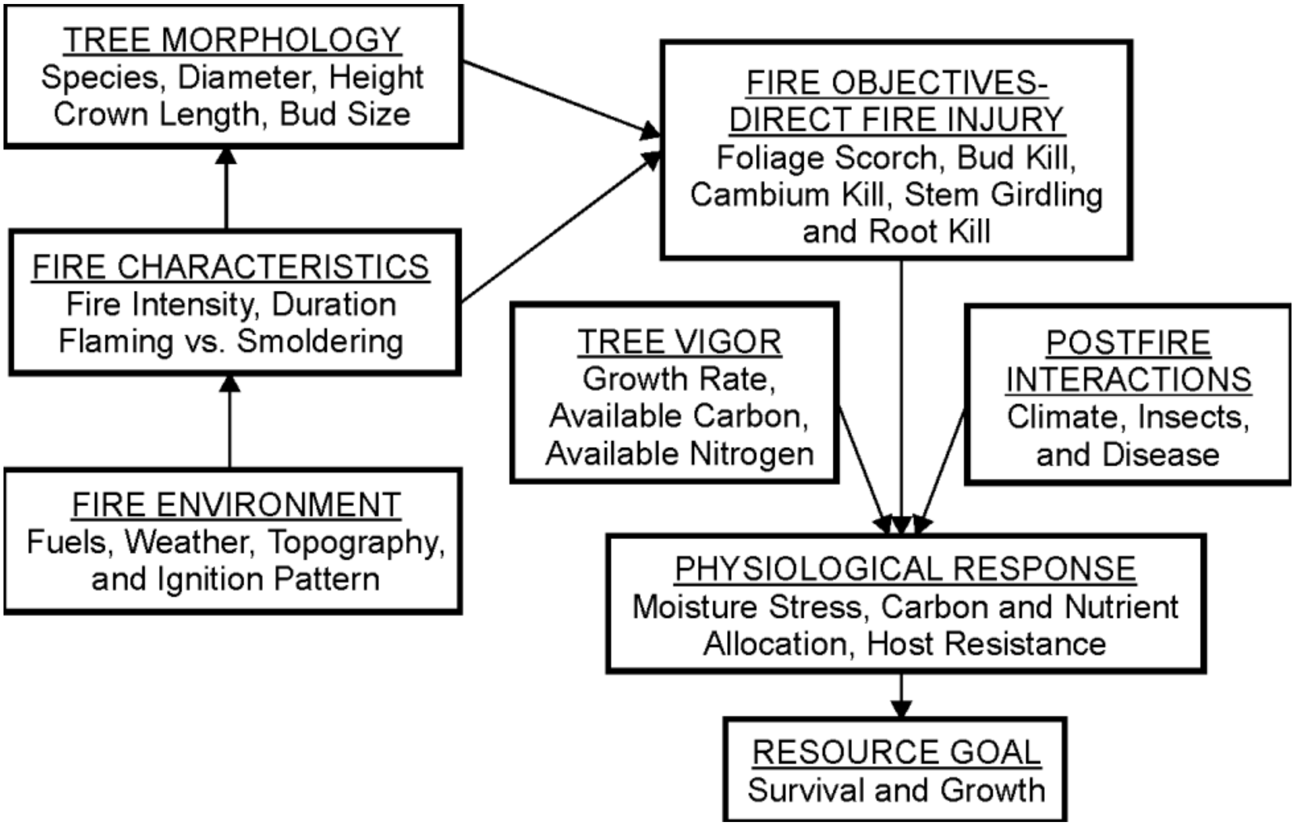

Fig. 1 Schematic illustrating the partial suite of factors that affect the behavior and effects of fire and necessary considerations in the achievement of fuel treatment and restoration goals in forests and woodlands.

The term *fire effects* simply refers to the observable alterations—permanent or temporary, reversible or irreversible—to the physical properties or biogeochemistry of the flora and fauna of terrestrial and aquatic ecosystems, the earth's atmosphere, and their implications to society. All fire effects may be relevant to varying degrees in any vegetation/fuel treatment. For prescription development purposes, it is important to clearly distinguish three classes of fire effects. First, the direct, first-order effects are those that result from combustion and heat transfer process during the burn. Combustion and heat transfer are the direct agents of change and vary with the specific fire environment (vegetation/fuel, weather, and terrain) as well as the kind of fire (heading fire, backing, fire, flanking fire) and the speed of application (c.f., Ryan 2002 for review). Direct effects to trees include crown, stem, and root injuries that the prescription is designed to manage (Fig. 1). Next are the indirect effects of fire. Indirect effects are those effects that are derived from or dependant on the fire's occurrence. If the fire had not occurred, indirect effects could not occur. Indirect effects are of two types: biophysical processes acting on the fire-altered environment and human responses. These include the post-fire biophysical processes such as nutrient cycling, insects, disease, and weather which affect the final outcome (second-order effects) as well as the real and perceived benefits or losses associated with the fire or its management (third-order effects). Tree growth and survival can be directly and indirectly affected by fire. Direct effects result in tissue death. Such death may be readily visible as in the case of crown consumption (burned foliage) and crown scorch (browned/dead foliage). However, bud, crown branch/twig cambium, stem cambium, or root injury may also occur. These latter injuries may be difficult to detect and quantify. The bulk of fire effects knowledge and decision support tools come under the first- and second-order effects and that is the primary focus of our synthesis.

Trees consist of three highly integrated organs: crown, roots, and stem or bole (Table 1). These organs have differing physiological functions and morphological properties that are important considerations in prescribed burning. First, there is the crown. For prescription purposes the crown is defined to include the foliage, buds, and branchwood. The crown is a resource assimilation organ that produces carbohydrates that are the source of all of the energy to meet the demands of the tree including maintenance, tissue growth, injury repair, and chemical defenses against insects and diseases. Second, there is the root system that supplies most of the raw materials (water and nutrients) essential for all metabolic functions and stores carbohydrates/starch. For prescribed burning purposes, the roots include the entire rhizosphere which is made up of the coarse storage and structural support roots, the fine 'feeder' roots, and the associated mycorrhizae. Third, there are the xylem and phloem of the stem that transport water and nutrients from the roots to the crown, and carbohydrates from the crown to the roots; the stem cambium allows the tree bole to expand in girth and is protected by the bark.

The stem also serves as a minor storage organ for water, nutrients, carbohydrates, and defensive chemicals. Under normal conditions in trees that produce annual rings, the stem increases in volume each year. However, new crown and root growth take precedence over stem growth in the hierarchy of carbon allocation (Waring 1987; Waring and Running 2007). The only allocation of carbohydrates that is of a lower priority to a tree is the production of defensive chemicals to protect against insects and disease.

Table 1. Tissue injury results from the interaction of critical fire environment variables with species and age/size morphological characteristics (adapted from Ryan 1998; Ryan et al. 2010).

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

Fire Injury – Resistance and Response

Living tissues of higher plants die when exposed to excessive heat. How long tissues can survive high temperatures depends on 1) the initial temperature of the tissue (i.e., starting air or soil temperature); 2) the amount and rate of heat supplied by the fire which depends on the amount of available fuel and its combustion rate.; 3) how well the tissue is insulated (e.g., by bark and/or soil), and 4) the tissue's specific heat capacity which is largely dependent on how much water is held within the tissue. Approximately, vascular plant tissues survive 1 hour at 50°C, 1 minute at 60° C, and 1 second at 70°C (Nelson 1952; Hare 1961; Peterson and Ryan 1986; Wade 1986; Botelho and Rigolot 2000; Rigolot 2004).

Crown injury is the most commonly observed fire injury. It is easy to visually detect and quantify. During acceptable prescribed burn conditions, crown injury generally determines overstory tree mortality, although as the days since rain increase and the duff dries, root and lower bole damage become increasingly important (Wade and Johansen 1986; Ryan and Frandsen 1991; Varner *et al.*2007). Crown injury occurs when heat energy released during combustion raises the temperature of a crown component above the lethal threshold of about 60°C.The level of damage depends on the amount of heat and the rate at which it is received from the combustion zone, the amount necessary depends upon the initial temperature of the foliage (Byram 1958). The initial leaf temperature is generally assumed to be the ambient air temperature which is a close approximation for conifer needles (VanWagner 1973; Peterson and Ryan 1986) although unpublished results of measurements by Paul Ryan in the early 1960's showed the uppermost canopy foliage of southern pines in direct sun could exceed ambient Fahrenheit temperature by over 20° (Wade personal communication 1965). Such observations could be important to predicting scorch height if subsequent research verifies the observation. Crown scorch has three components, death of foliage, death of branch/twig buds, and death of branch/twig cambia. Based on earlier work and for discussion purposes we distinguish between foliage kill, typically referred to as crown scorch (VanWagner 1973) and crown kill which refers to death of both foliage, buds, and twig cambia (Wagner 1961; Peterson and Ryan 1986; Ryan and Reinhardt 1988). Foliage is relatively small and poorly insulated. Thus it is relatively easy to kill and is **always** a precursor to bud and branch cambial damage within a given conifer species (Wade and Johansen 1986). Buds are somewhat more resistant to heat, particularly if they are large (e.g., *Pinus ponderosa*) and after bud scales have formed. Crown heat resistance depends on bud size, the amount of protection provided by needles and moisture content (Byram 1948; Wagener 1961; Peterson and Ryan 1986). Bud kill is more critical to tree survival than needle consumption and species with well protected buds are much less likely to be affected by fire (Wade 1985); Peterson and Ryan 1986). Experiments of lethal temperatures for needles and buds of *Pinus pinaster*, *Pinus nigra*, *Pinus brutia*, *Pinus halepensis*, *Cupressus arizonica*, *Quercus ilex*, and *Cupressus sempervirens*, showed that buds were less sensitive to heat than needles, and *Pinus pinaster* was a somewhat more heat resistant species (Alexandrian and Rigolot 1992; Rigolot 1992; Duhoux 1994). The cambium of branchwood is relatively resistant to heat.

Heat injury affects the physiology of the plants and the plant's physiological condition at the time of injury affects its response (Hare 1961; Kramer and Kozlowski 1972; Kozlowski 1985; Chambers *et al.* 1986). Tree response to crown kill varies with the vigor of the tree (Ryan 1990, 1998). Tree survival with respect to crown injury depends primarily on bud survival (Wagener 1961; Dieterich 1979; Wade 1985;Wade and Johansen 1986; Wyant *et al.* 1986; Ryan 1990; Hood 2010). Bud kill is more serious than foliage scorch because lost foliage cannot be replaced if the buds are killed. The crown may recover from foliar death if the buds survive and the branch contains sufficient non structural carbohydrates to initiate and sustain new foliar growth. Coniferous species can better withstand crown kill during the dormant season (Craignead 1940; Wagener 1961; de Ronde *et al*., 1986). *Pinus ponderosa* tree buds are large and relatively heat resistant (Wagener 1961; Ryan 1993, 2000) but quite vulnerable to fire damage in the growing season (Wagener 1961).

Bud kill generally occurs at a lower height in the tree than foliage scorch, particularly in trees with large or dormant buds (Fig. 2). In such cases the height of bud kill may be 2 or 3 meters less than the height of foliage scorch. In species with an indefinite terminal bud (e.g., *Thuia plicata*, *Juniperus* spp.) or with small actively growing buds (e.g., *Picea* spp. *Abies* spp., *Tsuga*, spp., *Pseudotsuga* spp.), buds are typically killed to the same height as the foliage (Peterson and Ryan 1986). In species with small set buds (i.e, leader growth has stopped and bud scales have formed) and those with large or shielded buds (e.g., *Pinus ponderosa*, *Pinus contorta*, *Pinus monticola*, *Larix occidentalis*) that are actively growing, buds will be killed to about 10 percent lower height than foliage. In species with large or shielded buds expect crown kill to be about 20 percent lower height than the height of foliage scorch once leader growth is complete and the buds are set.

Vigorous young trees often survive complete foliage scorch if the buds survive. At high crown kill levels surviving trees often exhibit little or no radial growth after burning. Reduced growth may last several years. At low crown kill levels, the remaining foliage may actually experience increased photosynthesis resulting in no growth loss (Wade 1985, 1986; Weise *et al.* 1987, 1989; Ryan 1993, 2000). In trees of average or better vigor, and in the absence of other significant injuries, empirical observation (Ryan 1998; Landsberg 1994) and physiological process modeling (Ryan 1990) suggests that:

- < 30 % crown kill – few problems, minor growth losses, minimal mortality
- 31-60 % crown kill – modest growth losses, increasing insect attack, modest mortality
- 61+% crown kill – major growth losses, insect attack and mortality rapidly increases.

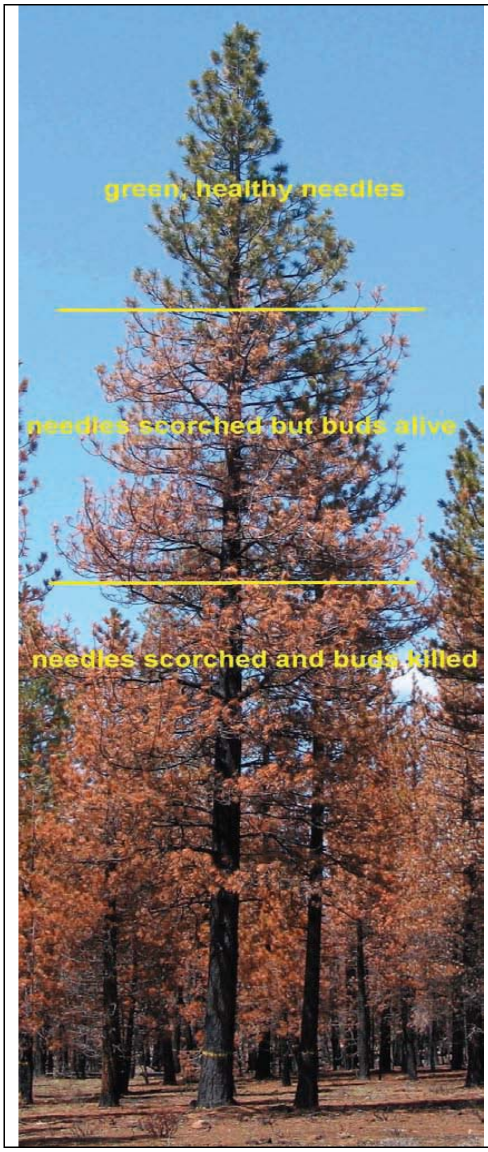

Fig. 2 Ponderosa pine showing the different types of crown injury. The uppermost, green portion of the crown was unaffected by the fire. The middle portion of the crown's needles were scorched and killed, but the buds survived. The lower portion of the crown's needles was scorched and both the needles and buds were killed. (from Hood 2010)

Crown scorch depends primarily upon the rate at which fine fuels ignite and burn. The most important fuels to consider when evaluating potential crown scorch are the stand's average mass of fuel ≤ 5 mm in diameter and its moisture content. Discontinuities such as openings in the forest canopy, ridges, and mid slope benches tend to favor ventilation of smoke. Scorch may be higher in these areas (Ryan 1982). It may be necessary to slow the rate of ignition around the edges of these areas. Heat from backfires normally does not reach high enough to significantly defoliate the trees. Headfires can be expected to casuse more injury in a given fire environment (vegetation/fuels, weather, and terrain) where crown base height is less than predicted scorch height. Currently, the best available technique for estimating the amount of foliage that will be killed in a fire is based on Van Wagner's (1973) scorch height model (Fig. 3). Figure 3L may be used to find the scorch height associated with a particular flame length and vice versa given a standard 37^{o}C day (e.g., summer wildfire conditions) and an observed or predicted mid flame wind speed. Crown scorch also depends on air temperature (Byram 1948; Van Wagner 1973) (Fig. 3R). Cooler temperatures yield lower scorch heights, which is of paramount importance when considering prescribed burning weather conditions as opposed to summer wildfire conditons. For example at 15^{o}C scorch height is 50 percent of that predicted in figure 3L. A variation of this model is also presented in Albini (1976), Reinhardt and Ryan (1988). Fig. 3 can be used to visualize flame lengths and wind speeds that will yield a specified level of foliar injury.

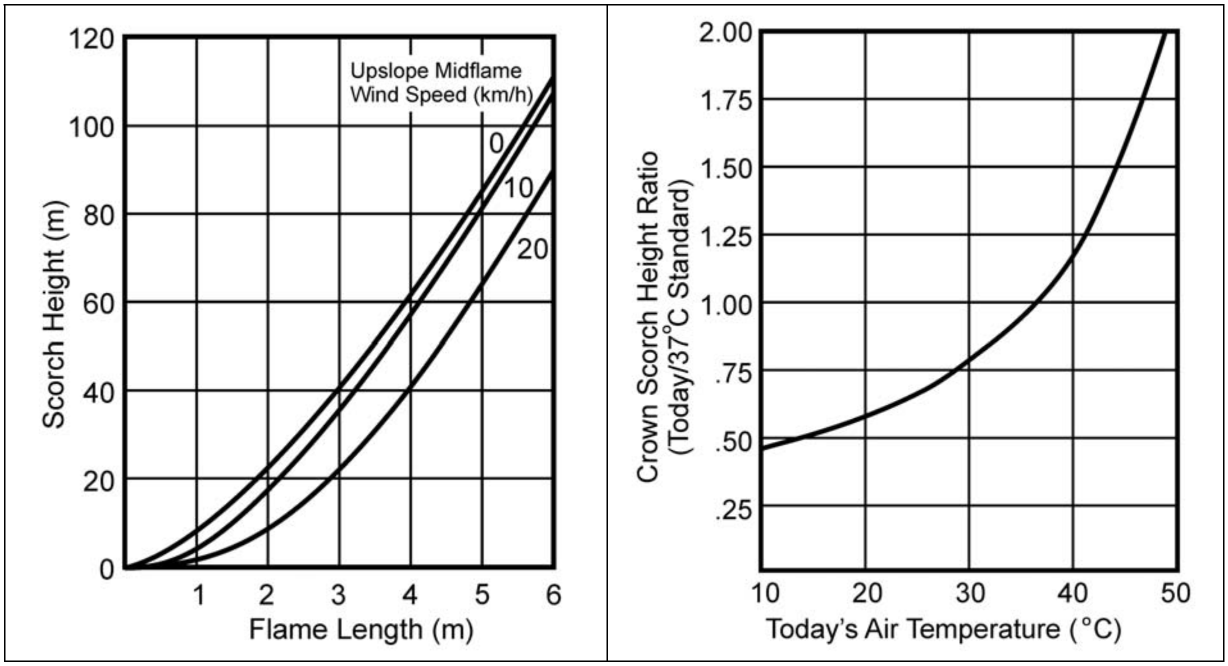

Fig. 3. Foliar scorch height (m) as a function of flame length (m) and wind speed (km/h) when today's ambient air temperature is 37^{o}C (left). Relative height of foliar scorch as a function of ambient air temperature ^{o}C (right). In the graph at the right ambient air temperatures < 37^{o}C correspond with height ratios <1, i.e., lower foliar scorch height. Conversely air temperatures > 37^{o}C correspond with higher foliar scorch. (adapted from Albini 1976, Cochrane and Ryan 2009)

Root damage is determined by the amount of heat conducted into the soil, but the depth of roots should also be considered. For purposes of prescribed burning roots include the root-crown, i.e., the area at the ground-line where the main stem transitions into the roots. The reason for including the root-crown as part of the rhizosphere as opposed to the main stem is because the fuel, fire behavior and heat transfer factors most critical to root-crown injury are more similar to those of the rhizosphere than of the stem exposed to the atmosphere above the forest floor during burning. Basal injury at the ground line is a common injury in fires (Ferguson *et al.* 1960; Ryan and Frandsen 1991; Hood 2010). Although basal injury may be caused by flaming in heavy coarse woody surface fuels at the base of the tree, injury is more typically caused by smoldering in the duff, particularly in long-unburned forests (Fig. 4). The amount of heat conducted downward into roots and laterally into the root-crown is dictated primarily by the amount of duff (fermentation and humus) consumed and soil properties, principally moisture content. Smoldering ground fires in conifer duff have been measured as having temperatures in excess of 400°C (Ryan and Frandsen 1991). Such temperatures have persisted for as long as 30 hours but durations of 3 to 6 hours are more typical. Thus, the amount and moisture content of the duff are the primary factors to consider in prescribed burning. In general duff moisture contents above 120 percent minimize duff consumption so should also minimize root injury. Below about 30 percent duff moisture content most duff is consumed so potential root injury is maximized. Between these is a range of intermediate duff consumption and potential root injury. Duff moisture content changes slowler than the litter. Diurnal changes in fine fuel moisture or changes in the ignition pattern are not likely to affect duff consumption and potential root injury unless they result in a patchy burn. If the surface fuels are ignited the duff beneath them will likely burn about as well at night as in the day. Light wind may improve duff burnout somewhat. If duff moisture is out of prescription it will require to wait for substantial precipitation or drying before there will be much affect on duff consumption and potential root injury.

There are few studies that have attempted to quantify fire-caused damage to fine and coarse roots in the soil. When roots are injured by fire, trees may grow slowly or die (Ryan, 1990; Abaimov *et al.* 2004), but root injury is rarely described due to the difficulty of assessing root distribution (Wade 1986; Swezy and Agee, 1991; Zeleznik and Dickmann 2004; Hood 2010; Noonan-Wright *et al.* 2010). The amount of root injury that occurs and its effect on survival and growth has not been quantified adequately.

Coarse or large roots function both as structural support and as carbohydrate storage organs. They are generally deep in most pioneer species and are not likely to be directly killed by fire unless considerable duff is consumed. Early successional conifers generally are shade intolerant and prefer a mineral seed bed. These species tend to be more deeply rooted than the late successional, shade tolerant species. In contrast late successional species tend to be shallow rooted. For example, *Sequoia sempervirens*, *Larix occidentalis*, and *Pinus ponderosa* naturally regenerate following fire and are generally deep rooted. *Pseudotsuga menziesii* and *Pinus contorta* are moderately deep rooted. *Pinus monticola* and *Pinus lambertiana* have an intermediate root depth. *Abies concolor* and *Abies grandis* are moderately shallow rooted. *Thuja plicata*, *Tsuga heterophyla*, *Picea engelmanni*, *Picea sitchensis*, and *Abies lasiocarpa* are shallow rooted species. *Pinus pinaster* has a deep-root habit with extensive lateral branches (Maugé, 1987). Seventy to ninety percent of the total root system is located below 60 cm under the surface soil level (Fischesser, 1981). Soil/site characteristics such as permafrost and high water table also affect rooting depth. Regardless of the initial rooting pattern most fine-feeder roots and their mycorrhizae are found in the duff and surface several centimeters of the mineral soil. As the duff gets deeper more roots are found in the organic soil layers. These are susceptible to injury by a prescription that results in heavy duff consumption.

When developing a burning prescription it is necessary to evaluate the potential for root injury by looking at the duff right around the base of the tree (Fig. 4). It is usually deeper and dryer than the average duff in the rest of the stand. This is because much of the needle litter and most of the bark flakes fall near the tree. The canopy intercepts rain until it is saturated. Only then does the rain fall through to the litter below. As a result the amount of rain received by the duff right beneath the tree is reduced. Usually long duration storms of 1 cm or more are needed to begin significant wetting of the duff mound beneath the tree. If the duff is deeper than 8 cm and dryer than 50 percent on an oven dry basis basal girdling may be a problem for all but the thickest barked trees. High mortality should be expected for shallow rooted species in any prescription that calls for more than 4 cm of duff consumption. Unless high mortality is a goal, fires causing deep ground char should be avoided. Mortality is not apparent immediately and may be delayed as sometimes occurs when smoldering duff either girdles the root crown or excessively prunes roots. Trees with sub-lethal tissue injuries have an increased likelihood of successful insect attack (Ryan and Amman 1993, Hood and Bentz 2007).

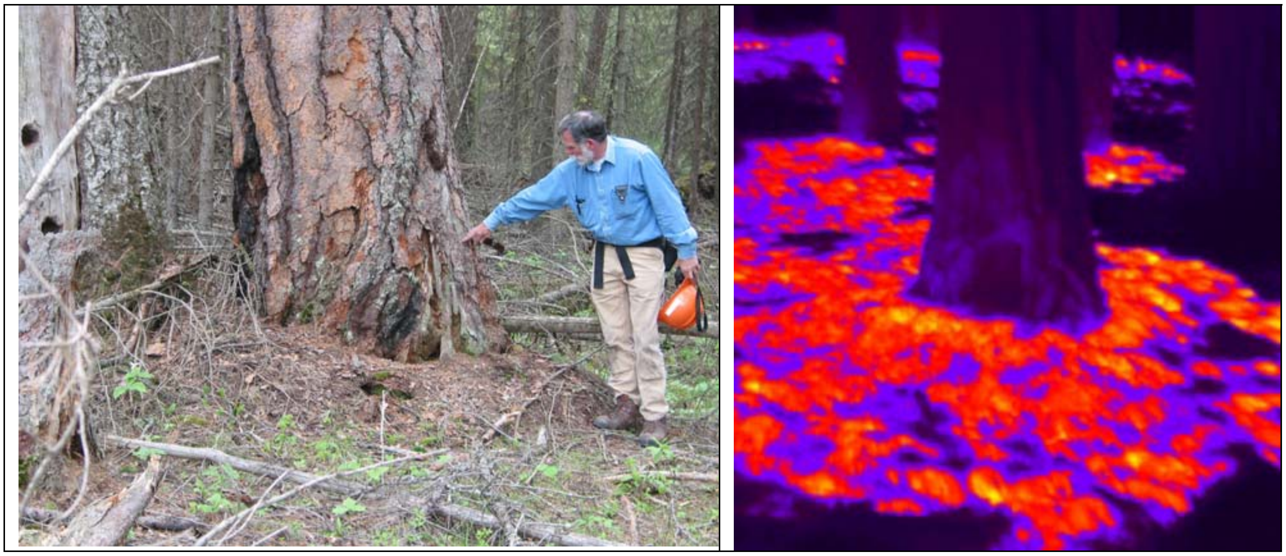

Fig. 4. Duff mound (l) beneath old growth ponderosa pine (*Pinus ponderosa*) in Glacier national Park, Montana and thermal infrared image (r) of smoldering duff (from Hood 2010)

For fire effects prediction purposes the stem includes the main bole/trunk above the duff surface where the primary heat source comes from flaming in surface fuels. Stem heating during a fire is complex heat transfer process involving radiation, convection, and conduction. First the surface of the stem is heated by radiation and convection. Then heat is transferred from the dead outer bark to living tissues (phelogen, phloem, and xylem) within the stem by conduction. Prediction of potential stem injury requires information about fire behavior in proximity to the tree and the tree's bark properties (Peterson and Ryan 1986; Rego and Rigolot 1990; Jones *et al.* 2004, 2006; Butler and Dickinson 2010). The two factors that are most important for determining the likelihood of trees suffering cambium injury are the thickness of the bark and the duration of burning in surface fuels. Bark thickness increases approximately linearly with stem diameter and it varies by species (Peterson and Ryan 1986; Ryan and Reinhardt 1988, Ryan *et al.* 1994a) (Fig. 5A). Resistance to stem injury varies with the square of the bark thickness (Fig. 6). The factors controlling the duration of burning include the fuel-bed particle sizes, arrangement, moisture content (Albini 1976; Albini *et al.* 1995a, b; Albini and Reinhardt 1997), and ignition pattern.

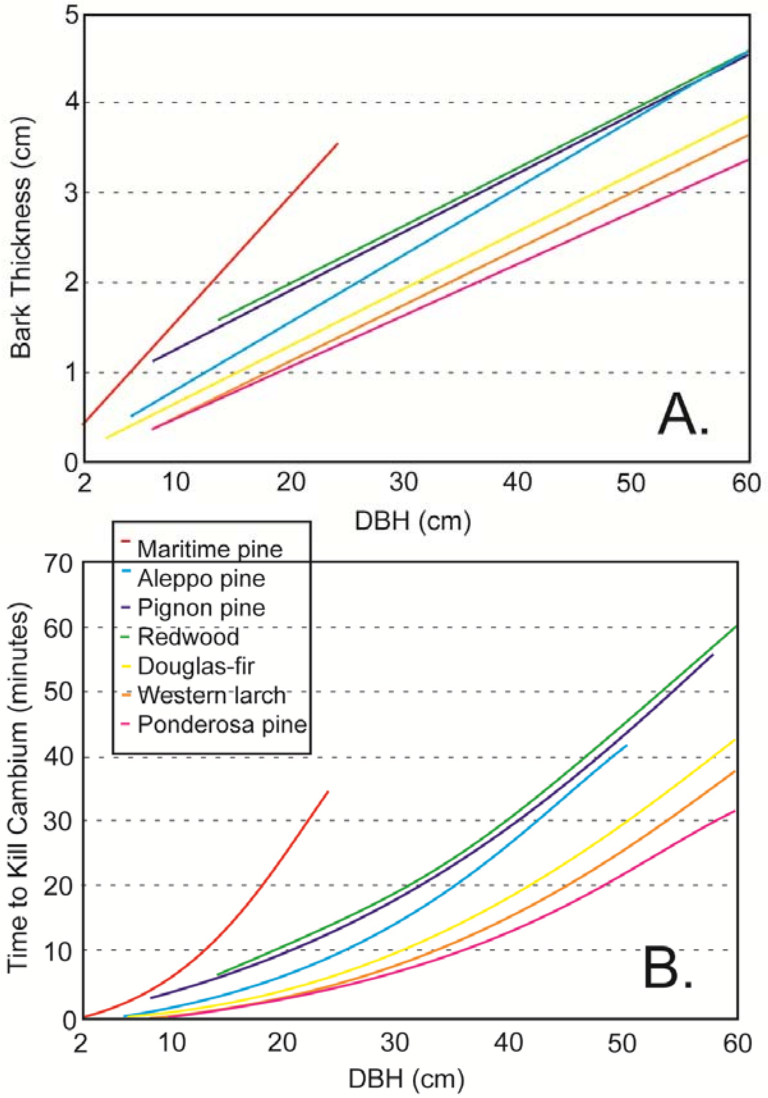

Fig. 5. Calculated critical time necessary to kill cambium for seven species from western North America and the Mediterranean Basin based on heat transfer relationships (from Ryan *et al.* 1994a). Maritime pine (*Pinus Pinaster*), Aleppo pine (*Pinus halepensis*), Pignon pine (*Pinus pinea*), redwood (*Sequia sempervirons*), Douglas-fir (*Pseudotsuga menziesii*), western larch (*Larix occidentalis*), and ponderosa pine (*Pinus ponderosa*).

The duration of burning that a tree can withstand is approximately 3 times the squared bark thickness (i.e., time to kill {min} = 3 x bark thickness $\{cm\}^2$) under common prescribed burning conditions (Peterson and Ryan 1986). The heating duration necessary to kill will be shorter for higher intensity fires and longer for very low intensity fires (Fig 6). Bark thermal properties vary somewhat from species to species but available literature suggests that the differences are unlikely to be a major factor in predicting the effects of fire when compared to the uncertainty in stem surface temperature.

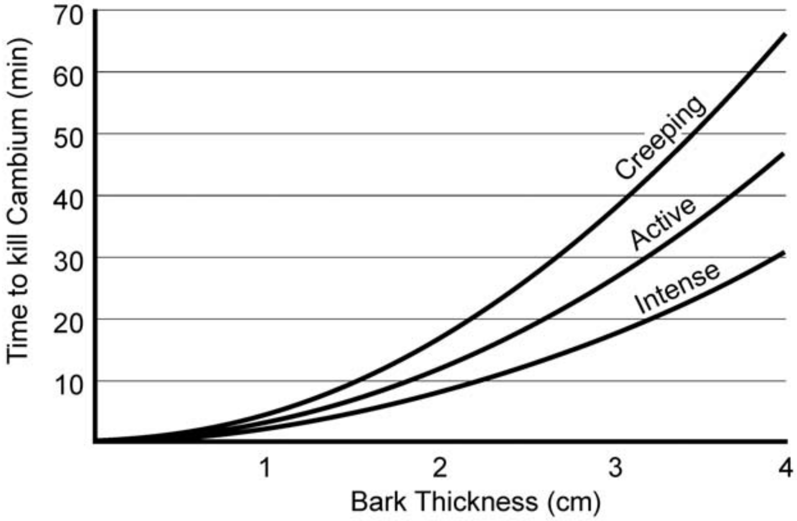

Fig. 6. The time to kill cambial tissue varies with the square of bark thickness and the difference between the stem's initial temperature (~ambient) and the stem's surface temperature due to radiant and convective heat transport from the flames. Stem surface temperature varies somewhat with the emissivity of the flames. Emissivity in turn increases with the flame depth as fire intensity increases until it approaches unity at around 1 meter flame depth. (from Ryan 1998, Cochrane and Ryan 2009)

If the duration of the fire is above the point on the curve representing your species and diameter in figure 5B, expect cambium injury. In general trees with bark less than 5 mm thick are poor candidates for survival in prescribed burns because it is difficult to consistently find suitable fuel and weather conditions for such short duration fires. Cambium beneath moderately thick bark (bark thickness 10 to 25 mm) is likely to survive light surface fires but not moderate surface fires or moderate ground char fires (e.g., where duff depth > 5 cm and dryer than 50 percent). Cambium beneath bark thicker than about 25 mm should survive most surface fires, with the exception of dry heavy coarse woody debris. The primary source of cambium damage on these larger trees results from smoldering ground fires in the duff. As previously pointed out basal girdling may be a problem if duff is deeper than 8 cm and dryer than 50 percent. If crown kill is less than about 30 percent and root injury is minimal, trees often survive with cambium killed in two quadrants up to breast height. If crown kill is between 30 and 60 percent trees often survive with dead cambium in one quadrant. The probability of survival is low for any tree with dead cambium on more than half of the circumference at breast height.

When sizing-up potential fuel situations the fuels within one- to two-meters are of primary concern. More distant fuels generally only cause problems when concentrated into piles that can burn for long durations. If the fuels are mostly ≤ 1 cm diameter expect the duration of burnout to be about 4 minutes. If there are a lot of 1 to 5 cm fuels expect the duration to be about 10 to 12 minutes. If there are enough 5 to 15 cm diameter fuels to make a sustained fire expect the duration to be about 20 to 30 minutes. Heavy coarse woody debris, i.e., large logs, is usually a problem only when they are resting against the bole or if clumped nearby.

Bark thickness, tree height, and crown ratio are all factors in determining susceptibility to fire injury and mortality(Fig. 7). Reinhardt and Ryan (1988) developed a graphical nomogram for predicting the effects of fire on conifers in western USA. This can be used in prescription development. The equations for the nomogram also are included in the fire effects section of the BEHAVE-Plus fire behavior and effects model (Andrews 1986; Heinsch and Andrews 2010, http://fire.org/index.php?option=content&task=category&sectionid=2&id=7&Itemid=26) FOFEM (Reinhardt *et al*. 1997; http://www.fs.fed.us/ccrc/tools/fofem.shtml), and CanFIRE (deGroot 2010) fire effects prediction systems. Numerous post-fire tree mortality models have been developed for the United States (Woolley *et al.* 2011), Canada (deGroot 2010), Europe (Fernandes *et al.* 2008; Catry *et al.* 2010), and Russia(Voynov and Sofronov 1976; Voynov *et al.* 1980; Abaimov *et al.* 2004).

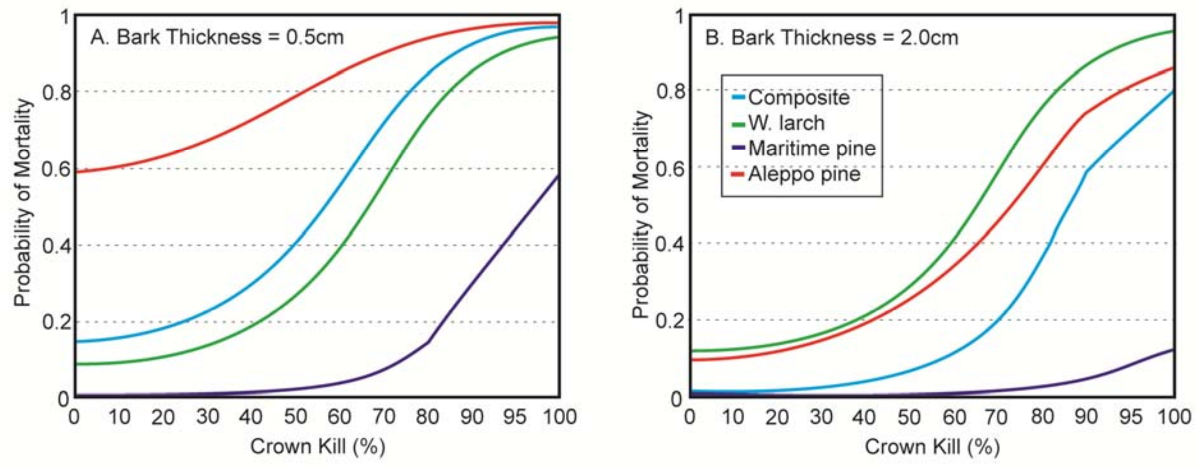

Fig 7. Predicted mortality for Aleppo pine (Pinus halepensis), Maritime pine (Pinus pinaster), western larch (Larix occidentallis), and a composit equation for all three species for thin (a) vs. thick (b) barked trees. (from Ryan *et al.* 1994b)

When conducting a prescribed burn it is necessary to size-up the fuels all around the tree and determine their burning characteristics. If, after having used a decision support aid (Reinhardt and Ryan 1988; Reinhardt et al. 2004; Fernandes et al. 2008, de Groot 2010) to calculate expected mortality the level of mortality is unacceptable, i.e., too high or too low then you have three choices: First, change the amount of fuel that can burn (commonly called available fuel) either by modifying the total amount of fuel (e.g., modify the harvesting, utilization, or removal standards to achieve the proper fuel load), or by modifying the moisture content of one or more elements of the fuel complex, raising or lowering moisture content to decrease or increase, respectively the amount of fuel consumed and energy released. Second, you change the prescribed weather conditions. Aside from effects due to fuel moisture changing the air temperature and wind speed will modify fire effects, particularly crown scorch. Diurnal changes in temperature and wind are not likely to have big effects on bole or root injury and the resulting growth losses or mortality. Third, you can modify the ignition pattern to either increase or decrease the amount of fuel on fire at any one time. For example, several strips ignited close together in time and space result in increased surface fire intensity. This increases crown scorch height but may result in bole damage to thinner-barked trees. Backing fires result in lower surface fire intensity but longer duration. This can result in lower scorch height but greater bole damage. When using strip head-fires intensity can be reduced without effecting duration by igniting one strip at a time and making the width of the burn strip less than the maximum flame zone depth. For example, if a free burning head-fire has, or is predicted to have a 5 meter flame zone depth, igniting strips less than 5 meters will result in lower flame lengths. Flanking fires result in varied fireline intensities. Initially, intensity is relatively low but increases as strips converge. This may be useful for increasing the amount of diversity on a burned area.

If the amount of fuel around a tree is too much for desirable leave-tree to survive, it is necessary to accept a higher level of mortality, change your prescription, or take supplemental measures to protect the trees. To change the prescription implies that you burn when duff and large woody fuels are wetter. Supplemental protection involves either pretreating the fuels or insulating the tree. Examples of fuel pretreatments include wetting the fuels using a fire hose or sprinkler; treating fuels with ground application fire retardants or foams; or removing fuel (Ryan and Steele 1989). Treating with fire retardant chemicals is not effective against large concentrations of logs or deep dry duff. The limits of usefullness of foams are presently unknown. Many new foam products recently have been developed for fire suppression but they have not been evaluated for their ability to protect trees. If you have large concentrations of fuels < 25mm diameter, think about burning when it is wetter unless only a few trees require clearing. Remove 25 mm to 75 mm fuels only if there is a clump of them. Remove large fuels within 2 times the log diameter (e.g., remove all 25 cm logs within 50 cm of the tree). It is difficult to say just how far to clear around a tree. Economics often dictates how much mitigation is possible. Usually 1 meter is sufficient but that depends on the amount of fuel and the thickness of the bark. The thinner the bark and the heavier the available fuel the further the fuel must be moved. When clearing fuel around trees broadcast the fuel to the side, never up hill or down hill (or on the windward side).

In western North America species with shallow roots also tend to have thin bark. This pattern also occurs throughout much of the Eurasian boreal forest (Melekhov 1980; Melekhov *et al.* 2007). It is unclear whether it is the dominant pattern in other parts of the world, particularly where genotypes have been planted off-site. It is consistent, however, to expect that species that evolved with infrequent fire would not invest the energy in producing thick fire-resistant bark if they were likely to suffer extensive root damage from a smoldering ground fire. Later successional species tend to be susceptible to both root and stem injury. As a result shallow rooted trees rarely survive surface fires with more than 50 cm high flames or those that consume more than the fresh litter (e.g., light ground char). The exception to this is when the fire is patchy and does not uniformly burn around the tree.

Scolytid bark beetles (Family *Scolytidae*) often attack trees following reintroduction of fire, compromising restoration goals. Because, stem growth and production of defensive chemicals are relatively low priority for a tree's carbohydrate allocation (Waring 1987, Waring and Running 2007) significant injury to crown or roots will result in reduced stem growth (radial or basal area growth). There will also be at least a temporary reduction in a tree's ability to defend itself from insects and disease. The relationships between fire injury and host susceptibility to insect and disease attack are poorly known. The need to understand beetle dynamics suggests we need more research and development in the physiological ecology of trees and insects.

Conclusions

Knowledge of the interactions between vegetation/fuels, fire behavior, and fire injury is integral to controlling direct fire injury thereby affecting the survival and growth of trees. Prescriptions for burning can be developed to minimize or enhance the type and degree of fire injury thereby favoring certain species and size classes of trees. It is important to realize, however, that most prescribed fires will cause at least minor injuries and temporary reductions in tree vigor and growth (Landsberg 1994). One of the premises of prescribed burning is that improved ecological conditions and the reduced risk of stand destroying wildfires justify investments in burning and minor growth losses. The application of prescribed fire beneath standing timber is challenging but integration of fire behavior knowledge with an understanding of the fire injury process and plant response to injuries can maximize desirable results.

When one looks across the globe at the near-infinite number fire environments it is easy to appreciate the impossibility of conducting robust empirical field studies on a large number of them. The many sites and species-fire relationship combinations, and the locally-variant social constraints argue in favor of taking a process-based approach to developing treatment prescriptions. Vegetation/fuels are highly variable in time and space leading to a wide range in fuel consumption/energy release and fire behavior. Fire weather is highly variable but the patterns are quite well known. Tree morphology is quite variable but there is a large body of physiognomic and mensurational data in the literature upon which one can draw inferences. While the body of knowledge on tree physiology is not robust evolutionary constraints argue that there are a limited number of plant responses to injury. The response of insects and diseases to fire injury to their host organisms has received only limited attention in the literature. By synthesizing our understanding of the biophysical processes associated with fire injury, survival, and growth we hope to develop interim models to guide safe effective fire use in vegetation/fuel treatments and restoration projects. We also expect to identify knowledge gaps that will help to prioritize subsequent research and development.

Acknowledgements

Any global review and synthesis of a complex topic such as fire’s effects on trees is built on the efforts of hundreds of authors working across the decades and continents. We acknowledge the contributions of many of those unsung, uncited authors who have contributed to our collective understanding. We particularly than thank Dale D. Wade for the depth and breadth of his knowledge and his suggestions for improving our work.

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