

THE SURVIVAL OF PINUS PONDEROSA SAPLINGS TO INCREASING LEVELS OF FIRE BEHAVIOR AND
IMPACTS ON POST-FIRE GROWTH

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AUTHORIZATION TO SUBMIT THESIS

This thesis of Wade Daniel Steady, submitted for the degree of Master of Science with a Major in Natural Resources and titled "THE SURVIVAL OF PINUS PONDEROSA SAPLINGS TO INCREASING LEVELS OF FIRE BEHAVIOR AND IMPACTS ON POST-FIRE GROWTH," has been reviewed in final form. Permission, as indicated by the signatures and dates below, is now granted to submit final copies to the College of Graduate Studies for approval.

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ABSTRACT

Improved predictions of tree species mortality and growth metrics following fires are important to assess fire impacts on forest succession, and ultimately forest growth and yield. In recent studies, North American conifers do not exhibit a binary response to fire where the tree either lives or dies; rather, there is a 'toxicological dose-response' relationship between fire behavior and the resultant mortality or recovery of the trees. Prior studies have not been conclusive due to potential pseudo-replication in the experimental design and time-limited observations. We explored whether dose-response relationships are observed in ponderosa pine (*Pinus ponderosa*) saplings exposed to surface fires of increasing fire behavior (as quantified by Fire Radiative Energy – FRE). We confirmed equivalent dose-response relationships to the prior studies. We further found that post-fire growth and mortality in ponderosa pine saplings corresponded to the amount of FRE applied and that, as with lodgepole pine (*Pinus contorta*), a low FRE dose could be applied that did not yield mortality in any of the replicates ($n=10$). These results suggest that land management agencies could use planned burns to protect similar fire-adapted tree species while eliminating unwanted species. Incorporation of these results into earth-system models and growth and yield models could help reduce uncertainties associated with the impacts of fire on timber growth, forest resilience, carbon dynamics, and ecosystem economics.

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DEDICATION

I would like to thank my parents and my girlfriend Kate, for all of their love and support. They never quit encouraging and pushing me to do the absolute best that I could. Without them, I would absolutely not be where I am, accomplished all that I have, or be who I am.

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1: INTRODUCTION

Globally, land management professionals are faced with increasing challenges of how to manage woodlands and forests in the face of larger and more destructive wildfires, while also increasing the use of planned fires as a pre-emptive mitigation approach [1, 2]. Planned (or prescribed) fires are an important management tool in many fire-prone ecosystems; they can remove brush and unwanted plant species [3] and help reduce fuel buildups that otherwise increase extreme wildfire and crown fire hazards. However, a challenge in using planned fires is determining what thresholds of different fire behavior characteristics (intensity, heat release, residence time, etc.) will yield the desired levels of mortality for various species/size classes [4, 5]. If desirable trees die from planned or wildfires, land managers must either allocate and invest more time, money, and resources to replanting and replacing them, or forgo having those species in that location for the rotation of that stand. If the desirable trees survive but are damaged, any reductions in vigor or growth could impact carbon stocks and timber yield for that area [6]. This could delay harvests or reduce the volume expected, resulting in a potentially lower profit margin.

Several recent studies have sought to address these challenges through controlled laboratory burns and planned landscape fire experiments where saplings to mature trees (2.5-40 years) have been exposed to surface fires at varying fire behavior levels and the associated mortality or recovery documented [3, 4, 7-12]. A common goal of these studies was to shift traditional *post-hoc* fire-severity research into a more controlled quantitative and mechanistic paradigm, by exposing plants to known amounts of heat and measuring the associated physiologic responses as a way to inform future model development [5, 7, 13]. These studies showed that the response of several North American conifer species exhibits toxicological dose-response relationships to fire, where increasing fire behavior as characterized by fire radiative energy (FRE) and flame lengths incident on the plants (the “doses”) results in increased probability of mortality and increased growth retardation (the “responses”) in the surviving saplings and trees [3, 4, 7-11, 14]. Research has demonstrated that these relationships persist at large spatial and temporal scales but that forest composition and pre-fire droughts produce complex interactions [10, 11].

A potential limitation of many of these studies is that plants are usually burned in groups, partly due to the nature of planned landscape fires. However, such an experimental design may lead to

pseudo-replication errors and also can produce spurious results due to extra heat incident upon target plants due to neighboring plants igniting and burning. Equally, some plants could shield others from radiation, resulting in some plants receiving less heat. A second limitation of prior studies is that limited species at young size classes (<1m height, < 5cm diameter) have been investigated [3, 4, 15], with the majority of research focused on mature trees [5, 16-20].

In the current study, we assess whether dose-response relationships between radiant heat incident on the plant and the plant mortality (and recovery) are apparent for *Pinus ponderosa* saplings burned in individual experimental laboratory fires. Prior studies, under laboratory conditions, have evaluated two conifer species that commonly co-exist with ponderosa pine: *Pinus contorta* (lodgepole pine) and *Larix occidentalis* (western larch) [4], whereas mature *Pinus ponderosa* (ponderosa pine) have been evaluated in landscape-scale planned fires [9, 18, 21]. However, only limited studies have evaluated young ponderosa pine saplings at landscape scales, [3, 12] and none to our knowledge, during controlled laboratory experiments.

As such, this paper seeks to test the following hypotheses:

- 1) H1: Increased FRE (*dose*) results in increased mortality (*response*) in *Pinus ponderosa* saplings up to several months post-fire.
- 2) H2: Increased FRE (*dose*) leads to decreased rate of growth (height and stem diameter) (*response*) of surviving *Pinus ponderosa* saplings up to several months post-fire.
- 3) H3: The *dose-response* relationships observed for *Pinus ponderosa* saplings are comparable to those observed for *Pinus contorta* [4].
- 4) H4: As hypothesized by [4], the *dose-response* relationships observed for *Pinus ponderosa* saplings during laboratory fires will exhibit a higher probability of mortality at lower dose levels as compared to similar age/size saplings burned during field experiments.

2: METHODS

TREES

A total of 50 ponderosa pine saplings were grown in a greenhouse at the University of Idaho's Pitkin Nursery Center for Forest Nursery and Seedling Research, located in Moscow, ID. The overall growing methodology from seed to the experimental age/size followed prior studies [4, 8, 22]. The saplings were grown in ~2.8 L pots for 2.5 years under natural light conditions and then subjected to surface fire in a combustion trial in a controlled laboratory setting. Following the combustion trials, they were maintained at the nursery (watered, fertilized, etc.) and evaluated until they entered dormancy, which was at approximately 4 months after the fire. Immediately prior to the combustion trials, the saplings averaged a height of 76.6 cm (S.E. = 2.1 cm) and a diameter at root collar of 0.54 cm (S.E. = 0.01 cm).

EXPERIMENTAL DESIGN AND FIRE EXPERIMENTS

The experiment was a randomized design; saplings were re-arranged each week to provide equal exposure to sunlight, water, and other environmental factors. All saplings were kept at the greenhouse until the experimental burns were conducted in June 2018. The saplings were watered to field capacity 24 hours prior to being burned. The combustion trials were conducted at the Idaho Fire Initiative for Research and Education (IFIRE) laboratory, a climatically controlled indoor environment adjacent to the Forest Nursery site where the saplings were grown and maintained.

Following [4, 11] the specific dosages of FRE were created by combusting dry (0% moisture content) fuel beds of pure western white pine (*Pinus monticola*) needles that had been thermally characterized through bomb calorimetry and assessed in prior experiments to have consistent rate of fire spread, combustion completeness, and radiant energy release by mass [4, 11, 23]. The needles were prepared by sorting them to remove impurities such as bark, moss, or leaves and then oven-drying them for 48 hours at ~100°C to ensure minimal fuel moisture content [24]. The needles were then distributed evenly across circular 1 m² beds. A uniform flaming front was achieved by igniting ~2g of ethanol with a filament wire situated at the edge of the bed. This remote ignition apparatus allows each experimental run to begin without people being present in the combustion chamber, thereby minimizing air movement associated with the opening and

shutting of doors. Two video cameras recorded each experimental burn, enabling maximum flame length to be visually estimated (Figure 1).

This study assessed four FRE dosages incident on the plants: 0.2 MJ m^{-2} , 0.4 MJ m^{-2} , 0.6 MJ m^{-2} , and 0.8 MJ m^{-2} . For each dosage (L) that included an unburned control, ten replicates (r) of similar-sized ponderosa pine saplings were used ($L=5$, $r=10$). The saplings were randomly divided into each group and assigned a uniquely numbered identification tag. The 0.2 MJ m^{-2} , 0.4 MJ m^{-2} , and 0.6 MJ m^{-2} FRE dosages were selected to re-assess inconsistent mortality results observed for other similarly sized conifer species subjected to a FRE dose around 0.4 MJ m^{-2} . For example, lodgepole pine saplings ($r=7$, [4]) exposed to a dose of 0.4 MJ m^{-2} exhibited 0% mortality, suggesting that lodgepole pine saplings may be able to wholly survive such low dosage fires. However, past assessments of western larch mortality at doses of 0.4 MJ m^{-2} have varied. In one study, well-watered western larch saplings ($r=7$, [8]) exhibited 33% mortality, while another ($r=7$, [10]) observed 0% mortality. In addition, drought stress has been shown to have a complex relationship with western larch mortality at 0.4 MJ m^{-2} , with severely stressed saplings whose foliage had senesced before exposure to fire exhibiting 14% mortality and moderately stressed saplings whose foliage had not senesced exhibiting 43% mortality ($r=7$, [11]). Inclusion of the 0.2 MJ m^{-2} and 0.6 MJ m^{-2} dosages additionally allowed us to assess whether, as with lodgepole pine and the more recent western larch study, the 0.4 MJ m^{-2} dose is a LOAEL (lowest-observed-adverse-effect-level) for mortality of ponderosa pine.

We based our maximum FRE dosage on data from prior studies that demonstrated near-complete mortality in similarly sized North American conifers at doses greater than 1.0 MJ m^{-2} [4]. We also included unpublished data from a companion study that assessed mortality of similarly sized ponderosa pine saplings at 0.7 MJ m^{-2} ($r=7$) and 1.0 MJ m^{-2} ($r=7$) using identical experimental procedures. To exclude potential pseudo-replication errors, each sapling was burned individually.

SAPLING MEASUREMENTS

All saplings were marked on the bole at the root collar to allow for consistent height and stem diameter measurements from the same location. Diameter at root collar (DRC) measurements were taken with calipers on all saplings immediately prior to combustion, and once per week post-burn

starting on the eleventh day after all trees were burned. Measurements continued for approximately four months until plant dormancy was observed. Total height measurements were taken each week with a tape measure from the same location on the stem to maintain consistency. The time lag between combustion and the initial post-burn measurements allowed the plants to equilibrate, as prior studies observed large amounts of noise in the data for up to 10 days following burns [4, 8]. In all cases, the pre-fire growth characteristics (DRC, total height) were measured in each sapling (cm) and percentage changes after the experimental burns were normalized to each individual sapling's pre-fire value. This accounted for any observed differences in diameter and height variability across all the saplings. In addition to pre-fire height and DRC, the height to live crown for each sapling was measured. At 28 days following the fire treatments, photographs were taken, and the percentage of crown volume consumed was visually estimated to the nearest 10%. Representative examples of the post-fire canopy condition across all the dosages are shown in Figure 2. Following prior experiments [4, 11], we assessed seedling mortality at 134 days post-fire, with the inability of meristems to regenerate shoots and complete death of the phloem and cambium beneath the bark assessed by a standard gardening cambium scratch test.

COMPARISON WITH LOGISTIC REGRESSION MODELS

Tree mortality was predicted using existing logistic regressions (eqn. 1) [6] and (eqn. 2) [25]:

$$P_{M(\text{general})} = \frac{1}{1 + \exp(-1.941 + 6.316(1 - \exp^{-bt}) - 0.000535c^2)}$$

(eqn. 1)

$$P_{M(\text{PIPO})} = \frac{1}{1 + \exp(-(-2.7103 + (c^3 \times 0.000004093)))}$$

(eqn.2)

Where, bt (bark thickness) = $0.1803 * \text{DRC (cm)}$ and the percentage crown volume (c) scorched is calculated by the following equation [26]:

$$c = 100(s * 3.28) * \frac{2(l * 3.28) - (s * 3.28)}{(l * 3.28)^2} \quad (\text{eqn. 3})$$

Where, l is the total length of the crown (m) and s is the length of the crown that is scorched (m). Tree mortality is usually assumed if $P_M > 0.5$.

Although these equations were designed for use across all age and size classes, they were developed using larger trees [6, 25]. Similar stem mortality logistic regressions have been developed for deciduous and other North American tree species [15, 18, 26-28]. Limited studies have explored the development of such mortality logistic regressions on young trees [3, 12, 14]. The relationship derived by [3, 12] is given by (eqn. 4):

$$P_{M(PIPO)} = \frac{1}{1 + \exp(-(-2.714 + (4.08 * L) + (-3.63 * H)))}$$

(eqn.4)

Where, L denotes flame length (cm) and H denotes the sapling height (cm) for ponderosa pine saplings less than 137 cm [3, 12, 20]. In contrast to eqn. (1) and eqn. (2) which produce continuous outputs, the form of (eqn. 4) forces a binary response of either live or dead.

DATA ANALYSIS

Arithmetic mean \pm standard error was calculated for all results. Post-fire height and stem diameter differences between treatment groups were compared with ANOVA and, if significant ($\alpha = 0.05$), then with Tukey's honest significant difference test.

3: RESULTS

Increasing FRE, which was associated with increasing flame length (Figure 1), resulted in greater crown scorch (Figure 2). Figure 3 shows the observed mortality of the Ponderosa pine saplings at 231 days post-fire and the results of the logistic regression equations (eqns. 1,2,4). The general form of the dose-response relationship (Figure 3a) follows that observed in the prior studies on other North American conifer species [3, 4, 7, 8, 11, 12, 16]. A 'no observed adverse effect level' (NOAEL) for mortality of 0.4 MJ m⁻² was present (i.e. no mortality was observed for each of the 0.2 MJ m⁻² and 0.4 MJ m⁻² dosages). In contrast, as shown in Figure 4, the NOAEL for post-fire growth was at 0.2 MJ m⁻² as all other dosages showed a significant impact on DRC and heights. At the opposite end of the spectrum, Ponderosa pine sapling mortality for this age class is effectively guaranteed at or exceeding dosages of 0.8 MJ m⁻².

Figure 4 shows the response of sapling relative DRC and height across all dosages for up to 4 months post-fire. Despite no observed mortality at the 0.4 MJ m⁻² treatment level (Figure 3a), Figures 4a and 4b clearly demonstrate, that although all these saplings were alive, they were growing at significantly reduced rates for several months after the fire. Specifically, the average stem diameter for the 0.4 MJ m⁻² saplings at four months after the fire was 0.54 cm ± 0.02 as compared to 0.65 cm ± 0.04 in the control saplings. Equally, the average height for the 0.4 MJ m⁻² at four months after the fire was 77.6 cm ± 5.9 as compared to 77.7 cm ± 4.5. In terms of absolute height growth over the 4 months post-fire, the 0.4 MJ m⁻² averaged 1.2 cm ± 0.2 and the control averaged 5.1 cm ± 1.0.

For relative DRC (Figure 4a), there was no significant difference ($p > 0.05$) between the control and 0.2 MJ m⁻² treatment at any point during the analysis. Relative DRC, for the 0.4 MJ m⁻², 0.6 MJ m⁻², and 0.8 MJ m⁻² treatment levels were all significantly lower ($p < 0.001$) than the control ~33 days post-fire. Stem shrinkage was observed in the 0.6 MJ m⁻² and 0.8 MJ m⁻² treatments immediately post-fire. Similarly, for relative height (Figure 4b), there was no significant difference between relative height ($p > 0.05$) between the control and 0.2 MJ m⁻² treatment at any point during the analysis (figure 4b). Although not significant, the average height value for the 0.2 MJ m⁻² treatment was 90.7 cm ± 4.5 compared to 77.7 cm ± 4.5 for the control. Similar to DRC, the 0.4 MJ m⁻², 0.6 MJ m⁻², and 0.8 MJ m⁻² treatment levels were all significantly different than the control ~40 days post-

fire. The loss of height observed in the 0.8 MJ m⁻² treatment was likely due to bud shrinkage and needle loss at the top of the crown. In terms of absolute DRC growth over the 4 months post-fire, the 0.4 MJ m⁻² averaged 0.03 cm ± 0.01 while the control averaged 0.12 ± 0.01.

4: DISCUSSION

The experimental results (Figure 3b) from our laboratory fire experiments do not produce similar dose-response curves to logistic regressions developed from data on large trees. In particular, the logistic regressions are not overly sensitive to fire behavior as they rapidly asymptote to high probabilities of mortality at the equivalent low FRE doses. In contrast to the large trees, a dose-response curve produced from the logistic regression, based on similarly sized ponderosa pine saplings burned in prescribed fires and wildfires, does produce a form that is similar to that observed in the current study [3, 12]. However, at the 0.8 MJ m⁻² dosage, this model (eqn. 4) predicts only 60% mortality as compared to 100% observed in the current study. This difference was hypothesized by [4] as ponderosa pine saplings burned in landscape scale fires will likely be more resistant to damage from fire given their roots are not bound and they may have been hardened due to surviving other stressors (i.e. environmental hardening). However, this difference could also be due to season of burn. This study burned saplings in June whereas [3] used data from dormant season burns (October-February). Prior studies have observed greater mortality in mature ponderosa pine after growing season burns than dormant season burns despite similar levels of crown scorch [29, 30]. In addition to season of burning, the threshold of fire behavior dose at which mortality is certain likely increases with the age and size of the tree [3, 9, 12, 31].

The form of the dose-response curve shown in Figure 4a has the same general form as that observed for similarly sized lodgepole pine saplings [4]. An important difference that was observed between the current study and [4] was that the post-fire response data for DRC exhibited clearer separation between the dosages.

These results suggest that saplings for similar conifer species of similar size would be expected to survive planned fires with low radiative energy (<0.4 MJ m⁻²). Although in lesser proportions, the majority (as indicated by the 'lethal dose 50% level', LD50 on Figure 3a) of the saplings would be expected to survive at FRE dosages less than 0.67 MJ m⁻². However, as observed in Figure 4, those that survive at this dose will experience significantly retarded growth. Prior research [10] has suggested that such growth reductions may persist for several years, but clearly research is needed to quantify the magnitude of this persistence to help improve growth, yield, and ecosystem models. Given land management professionals can already estimate the likely radiant heat release from a

planned fire treatment using common wildland fire combustion models, this information could be readily applied to estimate either how many saplings of a certain species may need to be replanted following fires or what level of fire is needed to remove unwanted understory tree species from the landscape. Equally, this data could be readily incorporated into existing growth and yield models that both predict tree mortality and adjust tree growth rates in trees that survive fires. For example, the USFS Forest Vegetation Simulator Fire and Fuels Extension assumes that when the fire scorch heights exceed the base of the tree crown (common during sapling fires), the surviving trees will grow at a reduced rate for the next time step [6]. However, this model assumes that tree mortality is dependent on scorch height, crown height, tree diameter, and species but does not explicitly use FRE [6].

5: CONCLUSIONS

To recap, the hypotheses we sought to test in the current study were:

- 1) H1: Increased FRE (dose) leads to increased mortality (response) in *Pinus ponderosa* saplings up to several months post-fire.
- 2) H2: Increased FRE (dose) leads to reduced growth (response) of surviving *Pinus ponderosa* saplings up to several months post-fire.
- 3) H3: The dose-response relationships observed for *Pinus ponderosa* saplings are comparable to those observed for *Pinus contorta* [4].
- 4) H4: As hypothesized by [4], the dose-response relationships observed for *Pinus ponderosa* saplings during laboratory fires will exhibit a higher probability of mortality at lower dose levels as compared to similar age/size saplings burnt during field experiments.

The current study supports each of these hypotheses. Specifically, we observed that increasing the FRE dose leads to increased crown scorch, mortality and increased levels of growth retardation responses in *Pinus ponderosa* saplings up to several months post-fire. The overall form of the dose-response relationship is comparable to that observed for similarly aged and sized lodgepole pine and western larch, providing more evidence that such dose-response data could be used as the basis of improved predictive models of wildland fire severity [5, 7, 13]. Lastly, the dose-response relationship was similar to that observed in [3, 12], except that the laboratory-based fires exhibited higher mortality levels than the field-based models predicted at dosages exceeding 0.6 MJ m⁻².

As described in [5, 32], the development of data describing the quantity of heat incident upon saplings and trees and the development of more dose-response relationships has enormous potential to improve modeling efforts to predict post-fire tree species mortality and recovery. Such modeling efforts could include not only improved fire-effects models, but also landscape-scale models that seek to predict growth and yield of timber or carbon stock changes due to fires. Equally, FRE and other large-spatial scale radiant energy products can be coupled with large-scale climate and vegetation dynamics data to improve assessing the vulnerability of forested goods and services under future fires [33, 34].

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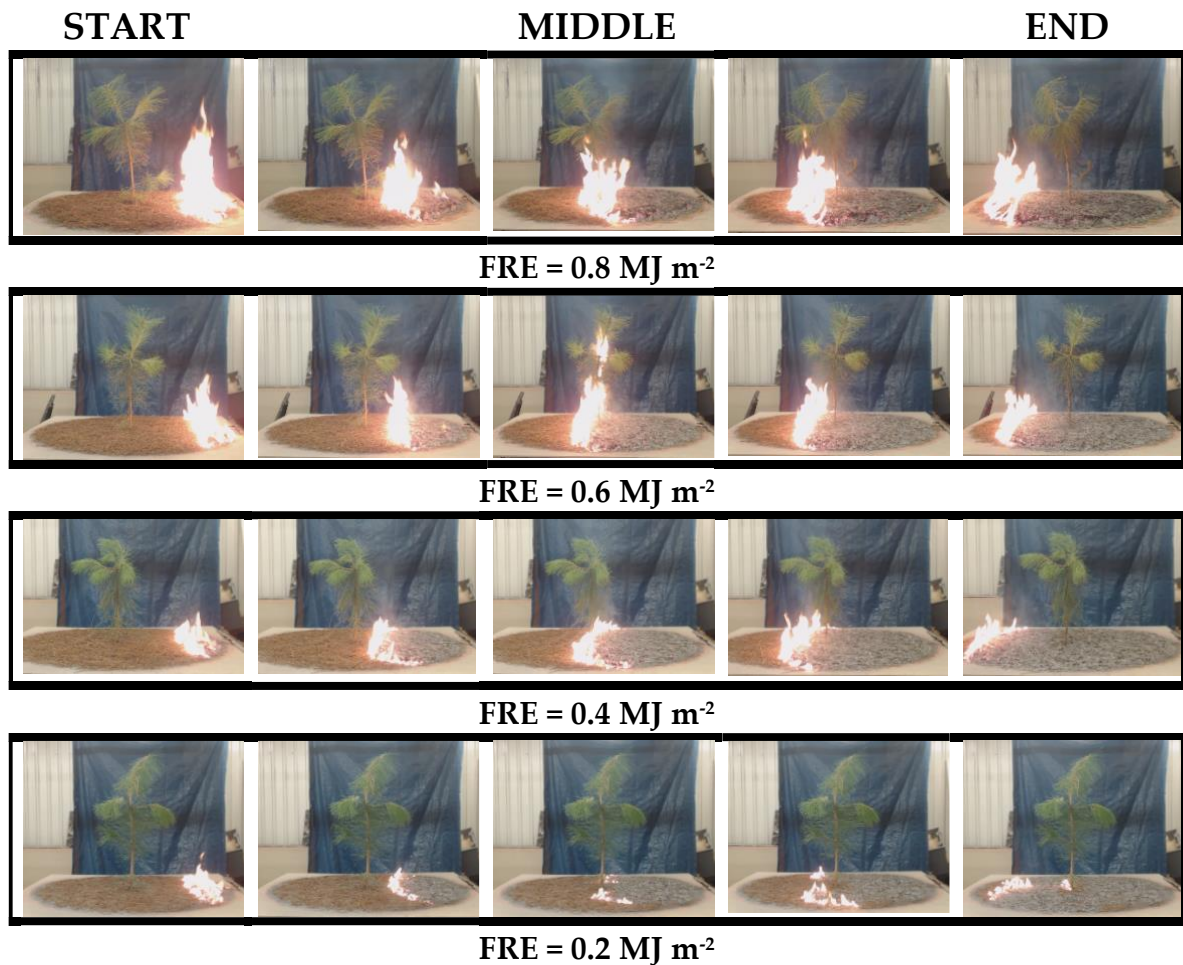


Figure 1. Time-lapse video images for representative saplings undergoing surface fires of increasing fire radiative energy (FRE) dose. Greater flame length as a function of FRE dose is clearly illustrated.



Figure 2. Representative examples of the health of the *Pinus ponderosa* saplings at the end of the experiment. From left to right, saplings represent the unburned control and treatments of 0.2 MJ m⁻², 0.4 MJ m⁻², 0.6 MJ m⁻², and 0.8 MJ m⁻². A clear visual dose-response is apparent, with the degree of surface charring and crown scorch increasing with increasing FRE dosages.

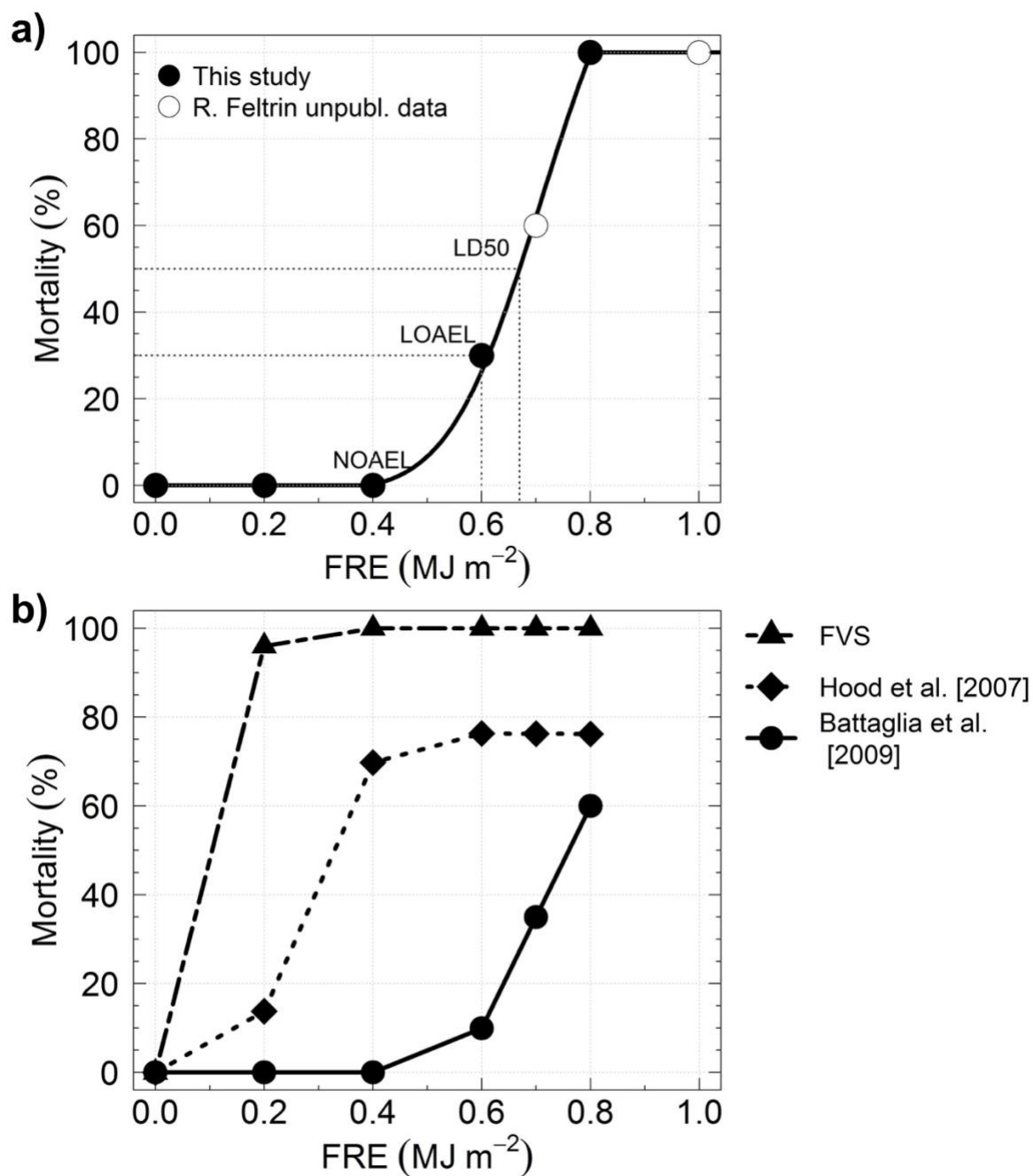


Figure 3. Mortality dose-response curve for ponderosa pine saplings. (a) Mortality as a function of FRE dose for 2.5-year-old ponderosa pine saplings in the current study. Unpublished data from a companion study (R. Feltrin unpubl. data) is also shown. (b) Equivalent dose-response curves of mortality as a function of the FRE dose applied in the current study. Ancillary pre- and post-fire data collected for each sapling were used to create these dose-response curves.

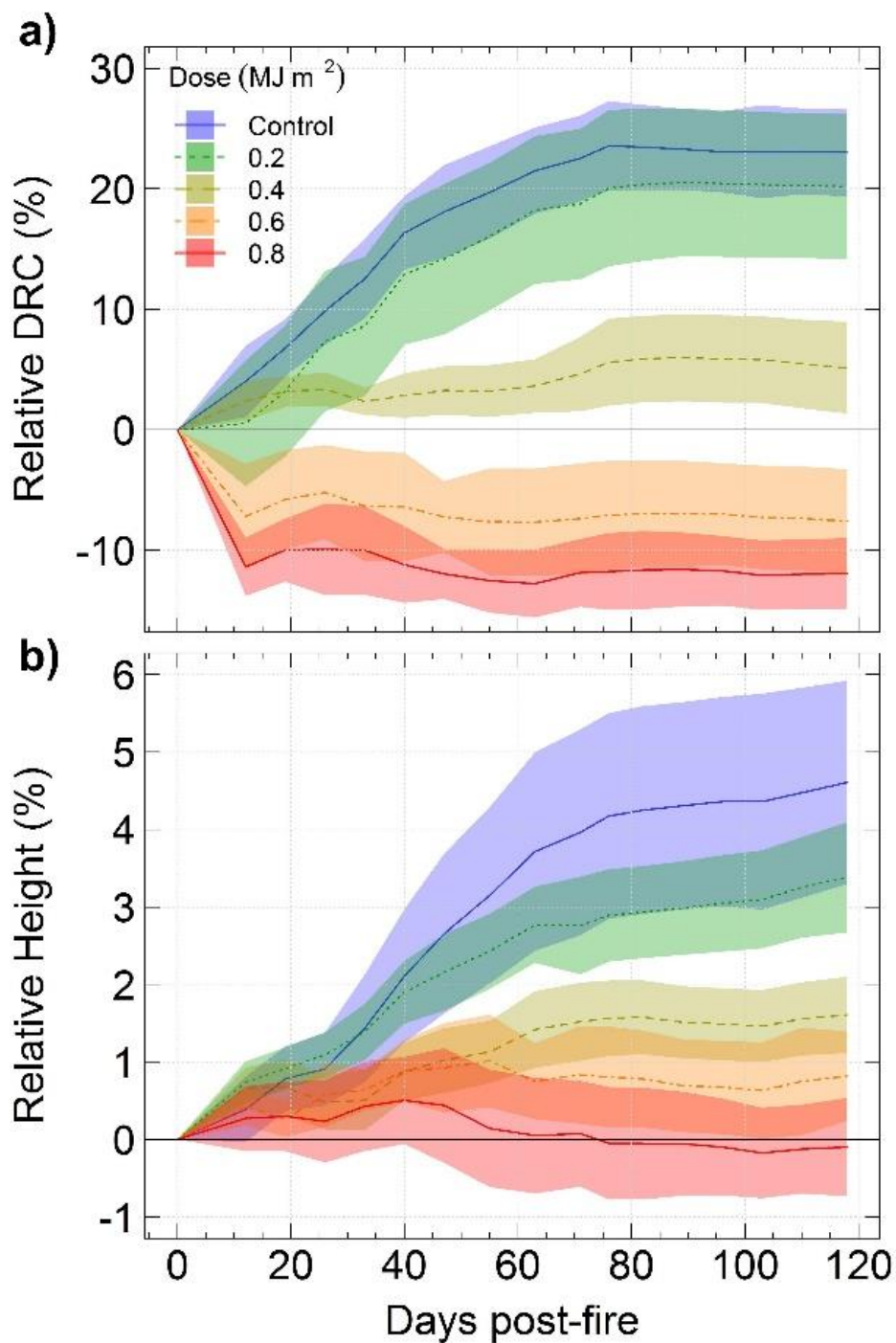


Figure 4. Relative changes in diameter at root collar (DRC) and sapling heights for each treatment group ($L=5$, $r=10$) for up to 120 days post-fire. The colored bands depict the 95% confidence interval for each treatment group. The lines represent the average values of the post-fire percentage changes for each group of replicates ($r=10$), where the colored bands represent the 95% confidence interval.