FINAL REPORT

Title: Towards improved quantification and prediction of post-fire recovery in conifers: Expanding laboratory fire radiative energy-tree physiology experiments to a mature forest stand

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Crystal Kolden
University of Idaho

Aaron Sparks
University of Idaho

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List of Abbreviations/Acronyms

FRFD	Fire radiative flux density, equivalent to fire radiative power (FRP) per unit area [W m^{-2}]
FRED	Fire radiative energy density, equivalent to fire radiative energy (FRE) per unit area [J m^{-2}]
MODIS	MOderate Resolution Imaging Spectrometer
NPP	Net primary productivity

Keywords

Conifers, fire behavior, fire intensity, fire severity, post-fire impacts, resin ducts, net primary productivity

Acknowledgements

We would like to thank the 2014-2015 University of Idaho Research Crew for their help with fieldwork. Additionally, the prescribed fires that were central to this work would not have been successful without planning and assistance from University of Idaho Experimental Forest staff - especially Rob Keefe and Brian Austin, Penny Morgan, Heather Heward, Zack Lyon, Connor Bell, and University of Idaho undergraduate students.

Abstract

Current assessments of the ecological impacts of fires, termed burn severity, investigate the degree to which an ecosystem has changed due to a fire and typically encompass both vegetation and soil effects. Burn severity assessments at local to regional scales are typically achieved using spectral indices (such as the differenced normalized burn ratio and the Relativized differenced Normalized Burn Ratio) derived from satellite remote sensing data before and following the fires. Although considerable efforts have been made to quantify post-fire burn severity across large spatial extents through spectral data, the explicit physiological link between fire behavior, tree mortality, and spectral reflectance is lacking, and inhibits prediction and quantification of tree mortality and recovery post-fire. Recent studies have highlighted the potential of linking fire behavior to plant ecophysiology as an improved route to characterizing severity, but research to date has been limited to laboratory-scale investigations. In this study, fire behavior was quantified at the tree- and landscape-scale and compared with post-fire growth, defenses, and productivity. Results show a clear dose-response relationship between peak fire radiative flux density (FRFD: W m^{-2}) and post-fire ponderosa pine (*Pinus ponderosa*) radial growth. Increasing levels of peak fire radiative power resulted in reduced post-fire radial growth. Permanent defense structures (axial resin ducts) were found to increase in density, size, and area per growth ring post-fire regardless of fire intensity. Satellite-based remote sensing observations of coniferous forests in the northwest United States were used to test the dose-response hypothesis at the landscape spatial scale. Similar to observations at the tree scale, satellite measures of forest productivity decreased with increasing fire radiative power. Species composition was demonstrated to influence the magnitude of productivity loss post-fire. Ultimately, this work provides critical first steps in building a framework to spatially characterize individual tree and forest condition post-fire, improving our understanding of the carbon cycle and ability to sustainably manage forests.

Objectives

The overarching objective of this work was to improve the characterization of severity by testing the following hypothesis: Increasing fire intensity dose increases the observed magnitude of tree physiological responses and associated spectral index differences. The objectives of this research were:

1) Quantify the relationships between fire radiative energy metrics, tree physiology, and spectral indices for large trees (greater in size than sapling) in a field setting.
2) Use relationships to create models for the quantification and prediction of tree mortality and surviving tree recovery.

Objective 2 was only partially met - there was not enough data to build tree mortality models (too few trees died). As such, we identified Objective 3 to further build on findings.

3) Assess relationships at the landscape scale utilizing remotely sensed data and stratifying by fire regime type.

Background

Recent evidence from North America of increased fire activity (intensity, frequency, and size) due to anthropogenic climate change (van der Werf et al. 2006; Moritz et al. 2014) underscores the need to improve our understanding of variable fire intensity impacts on ecosystem productivity and vigor at local to regional scales. These future changes are especially relevant to land managers as the prediction of fire effects (such as tree mortality and decrease in vigor) is necessary in the development of prescribed burn or wildland fire management plans (Butler and Dickinson 2010). Current assessments available to land managers, such as spectral index-based assessments using dNBR and RdNBR, only serve as a proxy for changes in cover of vegetation, char, and soils and do not quantify species mortality, tree physiological metrics (e.g. leaf area index, net ecosystem productivity), or recovery of vegetation vigor in the plants that survive the fires (Lentile et al. 2006; Hicke et al. 2003). Recent studies in plant physiology have observed that various tree physiology metrics respond to variations in heat associated with fires (Butler and Dickinson 2010; Michaletz et al. 2012; Smith et al. 2016, 2017). Specifically, increasing fire radiative energy density (FRED: MJ) and peak fire radiative flux density (FRFD: kW) incident on trees has been observed to result in reduced tree growth and increased mortality (Smith et al., 2017; Sparks et al., 2016). FRFD is the instantaneous radiative flux, which is strongly related to common field-based fire intensity metrics (Kremens et al., 2012), and its temporal integral is FRED. Coupling fire-physiology observations to landscape-scale remote sensing could help to overcome the limitations associated with current severity assessments, but research is currently lacking. The objective of this research is to reduce this major source of uncertainty by exploring linkages between physical measures of fire behavior, severity spectral indices, and plant physiology metrics related to function and mortality.

The expected benefits of this research include improved quantification of landscape-scale burn severity through biometrics such as net photosynthesis/net primary productivity, and predictive models that will help land managers with prescribed- and wild-fire planning. For example, the data produced from this quantification could serve as the basis for quantitative vulnerability maps for land managers (Smith et al. 2014) by identifying less vigorous stands that may be susceptible to secondary mortality (such as insects and disease). This work builds upon completed and ongoing laboratory research (Sparks et al. 2016, in review), and investigates relationships between increasing doses of fire radiative flux metrics (FRFD, FRED) with growth and physiological metrics including leaf net photosynthesis. This data will provide the foundation for future models of tree mortality and surviving tree vigor. As FRE is strongly correlated with total energy release from a fire (Freeborn et al. 2008), these models could be incorporated with the energy release component (ERC, units: Btu ft^{-2}), a National Fire Danger Rating System (NFDRS) output that calculates the potential energy per unit area based on fuel load and live/dead fuel moisture, to help predict future fire effects such as tree mortality. Ultimately, the expected benefits will help address the JFSP "post-fire recovery" topic area by improving: 1) our understanding of physiological changes in trees post-fire based on fire intensity metrics, and 2) our ability to quantify burn severity at landscape scales.

Materials and Methods

Stand-scale experiments to address Objectives 1 and 2.

Three even-aged, ponderosa pine (*Pinus ponderosa*) dominated stands at the University of Idaho Experimental Forest were chosen for this study, ranging in elevation from ~880-950 m. In June 2014, approximately two hectares of each stand was mechanically thinned using a boom-mounted brushing head. All understory shrubs were chipped and the overstory ponderosa pine was thinned to a target spacing of 6 m and chipped. Prescribed burns were conducted on two consecutive days in late October 2014 in one-half of each stand to reduce surface fuel loadings. Prior to the prescribed burns, nine 5 m by 7 m rectangular plots were selected from a 60-plot grid established as part of an ongoing study (Figure 1). The nine plots were deliberately selected to exhibit a wide variability of slopes, aspects, fuel loading, and moisture content to facilitate a large range of potential fire behavior conditions. Plots were ignited with a drip torch on the downhill side to establish a uniform head fire flaming front, with ignition lines separated by ~8m (Figure 2). FRFD was quantified using tower-mounted, dual-band infrared radiometers (centered in each of the nine plots – see Figure 2) and methodology from Kremens et al. (2012). FRED was calculated as the temporal integral of FRFD observations.

At 1.5 years post-burn, a mortality and tree health survey was conducted in all prescribed burning stands. Increment cores were collected at ~1.37 m above the ground from all (n=31) trees within the nine study plots (Figure 1) and from trees in the unburned half of each stand (n=31) (location not shown). Ring widths were measured using a Nikon SMZ800 microscope equipped with a Velmex micrometer and used to calculate relative growth (% deviation from mean 3-year pre-fire growth), calculated as [($Growth_{yrX}$ –$Growth_{avgPrefire}$) / $Growth_{avgPrefire}$]. Images of each core were obtained using a SPOT Idea 5 MP camera and processed using ImageJ software to quantify axial resin duct size and area. Data were grouped into classes using equal-width bins for each fire radiative metric (e.g. $FRFD_{peak}$, FRFDμ, FRED) and differences between groups were assessed using ANOVA and post-hoc Tukey's Honest Significant Difference test ($\alpha = 0.05$).

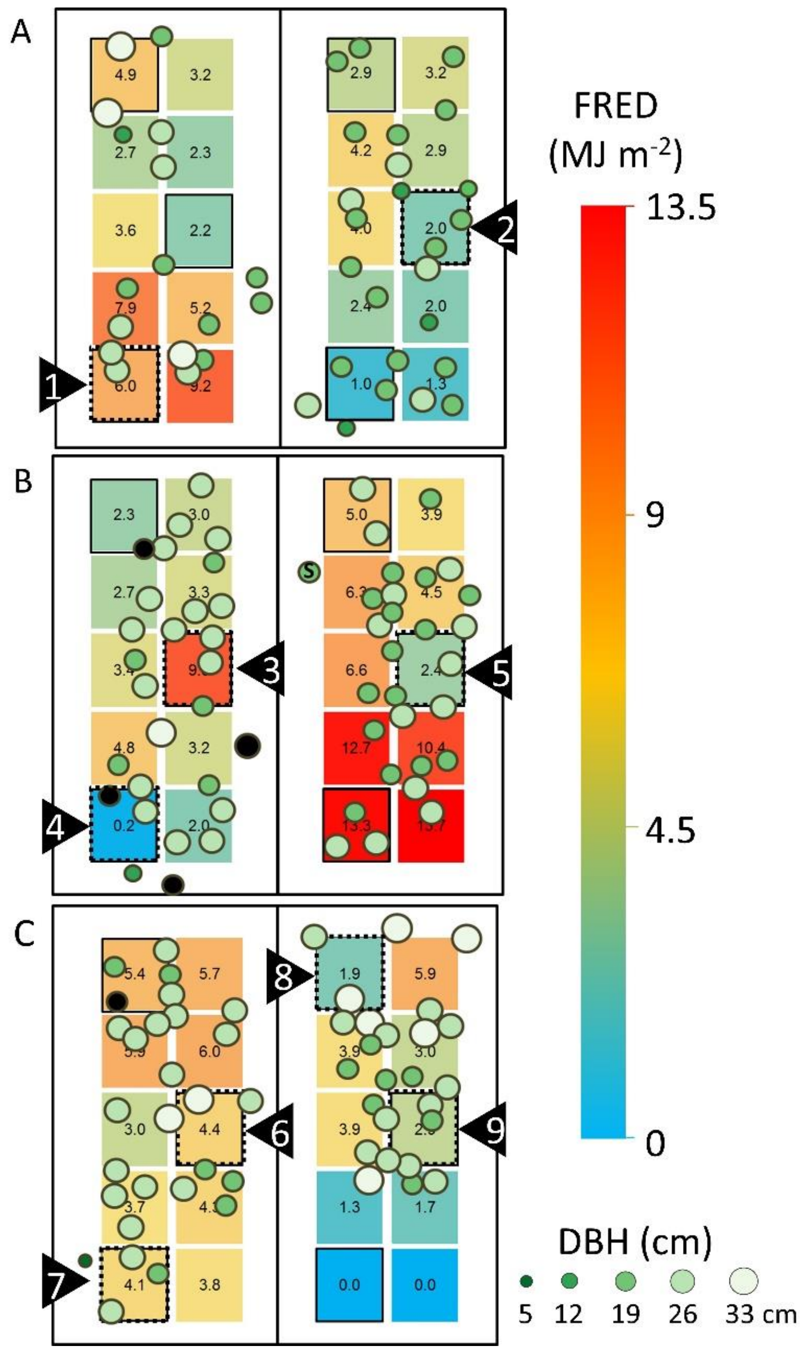

Figure 1. Stem map of ponderosa pine within the three stands at the University of Idaho Experimental Forest. Trees are displayed by diameter at breast height (DBH) class along with observed and modeled Fire Radiative Energy Density (FRED) (stands A-C). Numbered plots (1-9) with dotted outlines indicate where consumption and Fire Radiative Flux Density (FRFD) were measured. Solid plot outlines indicate plots where fuel consumption was measured and FRED was modeled. Consumption and FRED were modeled for plots with no outlines using the linear relationship between FRED and consumption. Trees outside of the plots, but within 2 m are shown for illustrative purposes. Black and 's' trees indicate dead and stressed trees, respectively. Source: Sparks et al. 2017.

Figure 2. Ignition of instrumented plot in prescribed fire experiments in ponderosa pine stands at the University of Idaho Experimental Forest. Fire intensity was quantified via fire radiative flux density using tower-mounted dual-band infrared radiometers (photo center) and methodology detailed in Kremens et al. (2012).

Satellite remote sensing observations to address Objective 3.

Observations from the MOderate Resolution Imaging Spectrometer (MODIS) for fifteen large wildfires in the northwestern United States were used to quantify relationships between FRP, FRE, and coniferous forest net primary productivity. The fire-affected forests were classified into three groups depending on their pre-fire dominant vegetation (derived from LANDFIRE Existing Vegetation Type product): fire-resistant (forests dominated by trees that typically survive low-intensity fires), fire-susceptible (fires that do not typically survive low-intensity fires) and mixed (forests comprised of both fire-resistant and fire-susceptible species). The MODIS 1 km NPP product (MOD17A3) was used to characterize changes in productivity within and between each fire. The MODIS 1 km Level 2 active fire product (MOD14, MYD14) was used to quantify FRP distributional statistics (peak, mean, interquartile range) and FRE.

Fire-affected pixels were grouped by FRP and FRE percentile classes (0-25, 25-50, 50-75, 75-100). Unburned pixels outside the fire perimeter were chosen to represent ‘control’ pixels. Relative changes in NPP for all FRP/FRE percentile groups (and control) were calculated as:

[(NPP$_{yrX}$ –NPP$_{avgPrefire}$) / NPP$_{avgPrefire}$]. Control pixel average values were subtracted from the fire-affected pixel values to account for interannual variability not caused by the fires. Differences between FRP/FRE percentile groups were assessed using ANOVA and post-hoc Tukey's Honest Significant Difference test ($\alpha = 0.05$).

Results and Discussion

Stand-scale experiments to address Objectives 1 and 2.

Overall, trees in the burned plots experienced decreased post-fire growth than unburned control trees (Figure 3a). Increasing fire radiative power resulted in decreased radial growth of fire-affected ponderosa pine (Figure 3b). Unlike prior sapling experiments (Smith et al. 2016, 2017; Sparks et al. 2016), there was no relationship between FRED and tree growth or mortality. There are several factors that could account for this discrepancy. First, the trees in these Rx burn experiments were larger and had more-developed fire-resistant traits (e.g. thicker bark, higher crown base height) than saplings previously burned in the laboratory. Second, fire behavior was dominated by smoldering combustion, whereas laboratory burns were dominated by flaming combustion. The heat dose was distributed over a longer time period compared to the laboratory fires and could have led to reduced damage. Results also suggest that other modes of heat transfer (e.g. convection) associated with higher intensity fire behavior (e.g. higher fireline intensity and fire radiative power) may be responsible for reductions of growth post-fire. For example, in the plots with high peak FRFD, flame lengths exceeded 1.5 m, which could deliver substantial convective heat flux to the tree crowns via hot gases rising above the flames.

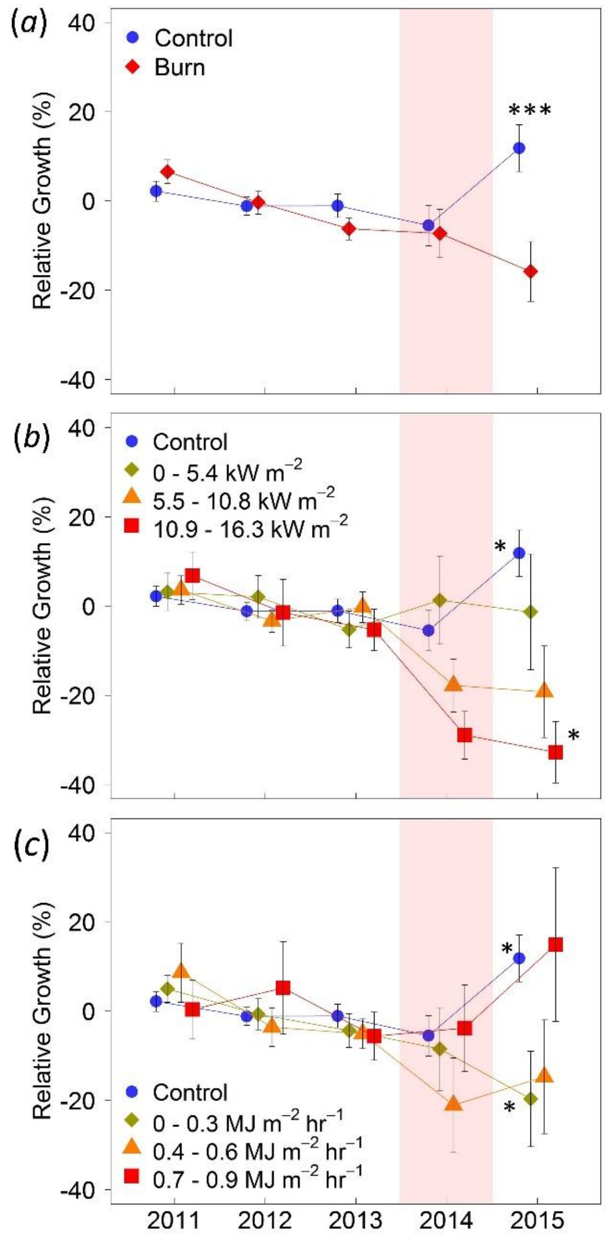

Figure 3. Ponderosa pine relative radial growth (mean ± SE) by treatment (a), Fire Radiative Flux Density (FRFD) class (b) and normalized average Fire Radiative Flux Density (FRFD$_{\mu}$) class (c). Relative radial growth is calculated as [(Growth$_{yrX}$ –Growth$_{avgPrefire}$) / Growth$_{avgPrefire}$]. Red highlight indicates year that prescribed fires were conducted. Asterisks indicate significant differences: * p<0.05; ** p<0.01; *** p<0.001. Source: Sparks et al. 2017.

Increased resin duct density, average size, and total area per growth ring occurred regardless of fire intensity (Figure 4). These observations agree with the majority of ponderosa pine studies, which show post-fire increases in resin duct defenses regardless of fire intensity (Feeney et al. 1998; Perrakis and Agee 2006; Davis et al. 2012; Hood et al. 2015). This suggests that ponderosa pine may have reduced post-fire vulnerability to secondary mortality agents, such as bark beetles.

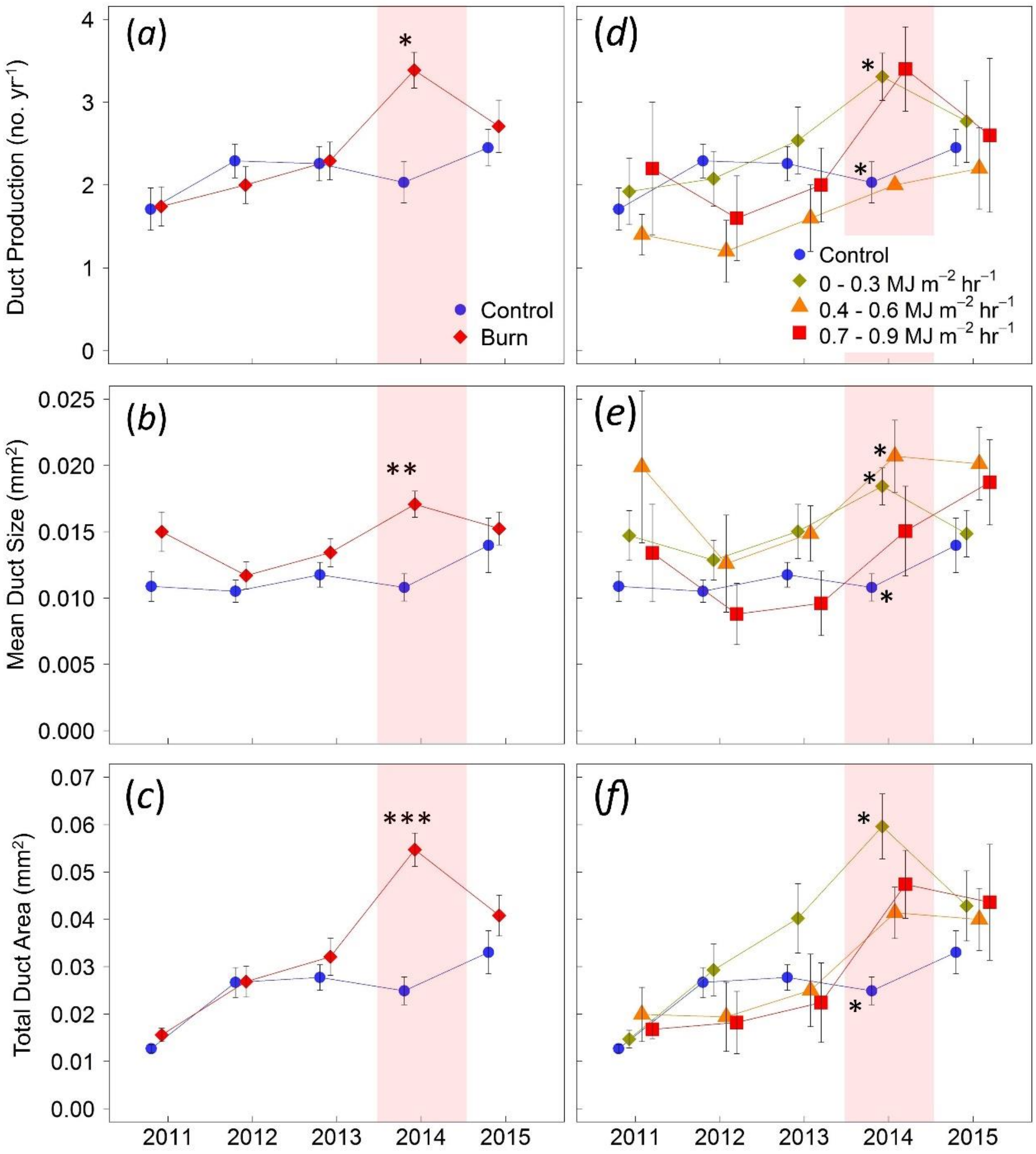

Figure 4. Ponderosa pine resin duct production (mean ± SE) by treatment (a) and normalized average Fire Radiative Flux Density (FRFDμ) class (d), mean resin duct size by treatment (b) and FRFDμ class (e), and total resin duct area by treatment (c) and FRFDμ class (f). Red highlight indicates year that prescribed fires were conducted. Asterisks indicate significant differences: * $p<0.05$; ** $p<0.01$; *** $p<0.001$. Source: Sparks et al. 2017.

Landscape-scale satellite remote sensing observations to address Objective 3.

Similar to observations at the tree scale, landscape-scale measurements of forest net primary productivity decreased with increasing fire intensity, regardless of species composition (Figure 5). However, forests dominated by species with higher fire-resistance displayed lower reductions in post-fire net primary productivity, highlighting the importance of species composition in accounting for post-fire carbon dynamics. NPP reductions at 1-2 years post-fire were comparable to aboveground NPP differences in similar forest types between unburned and burned forest stands quantified via field measurements (Irvine et al. 2007). Notably, the dose-response relationship remained years after the fire (up to a decade in some cases) indicating that initial fire intensity has a legacy effect on carbon dynamics. The majority of FRP/FRE percentile groups did not recover to pre-fire NPP, despite an average observational period of 8.4 years.

A growing number of studies have observed mechanistic links between fire intensity (or proxies of fire intensity such as crown scorch) and post-fire mortality and productivity in saplings (Sparks et al., 2016; Smith et al., 2017) and larger trees (Ryan and Reinhardt, 1988; Hood et al., 2007; Sparks et al., 2017). The remote sensing observations in this work, building upon tree-scale studies, suggest that such linkages scale to the landscape scale. With further study, a hypothetical framework could potentially be used to spatially characterize individual tree and forest condition post-fire (Figure 6).

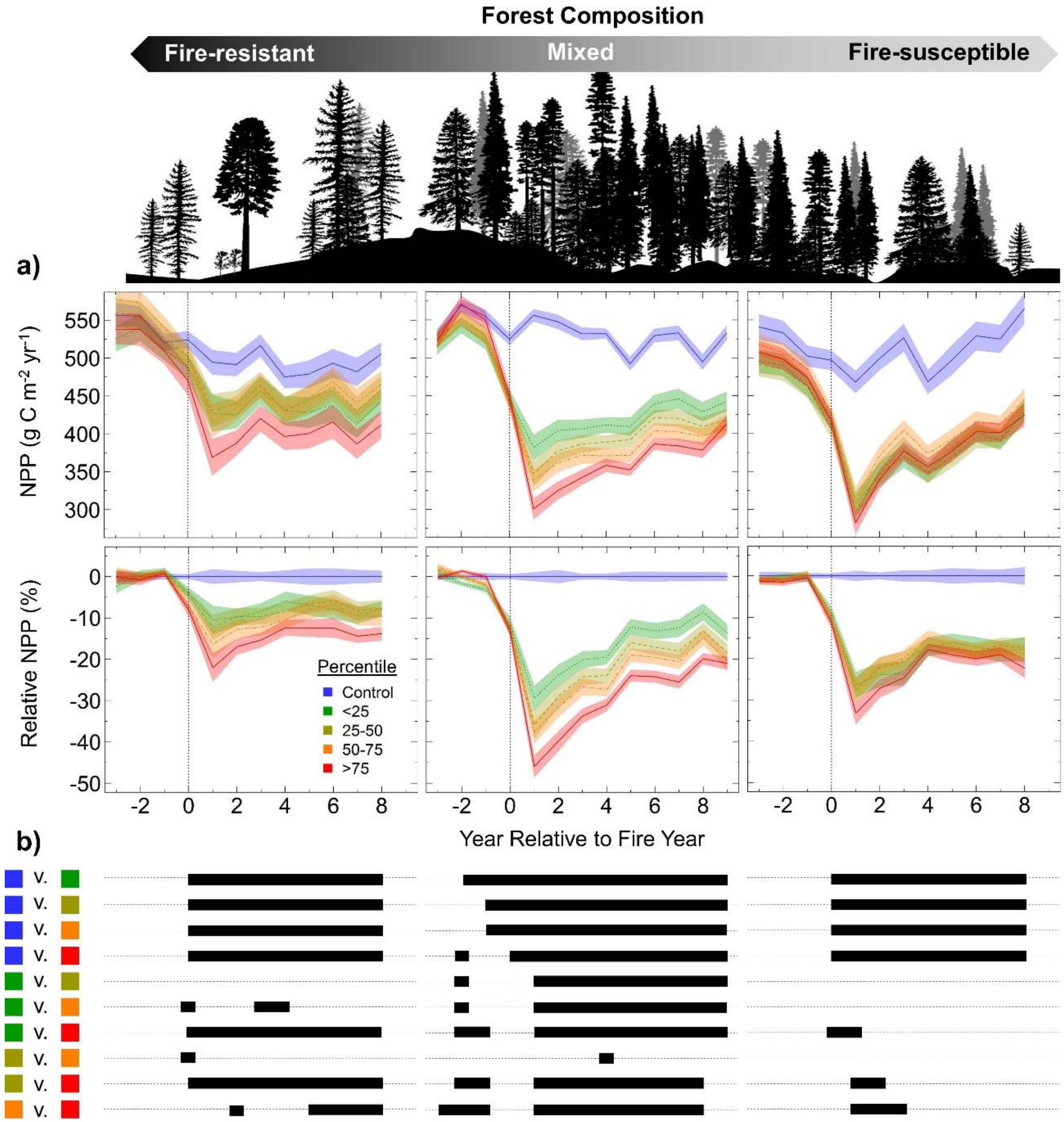

Figure 5. Fire intensity impacts on net primary productivity. a) FRE dose impacts on absolute NPP (g C m^{-2} yr^{-1}) and relative NPP (%) observed in forests dominated by species varying from fire-resistant to fire-susceptible (first column – third column). NPP is grouped by FRE percentile classes and shading represents 95% confidence intervals in all panes. Grey dotted line marks fire year. b) Results from ANOVA with a post hoc Tukey's honest significant difference test (α = 0.05). Black bars indicate years where relative NPP groups differed. Source: Sparks et al. 2018.

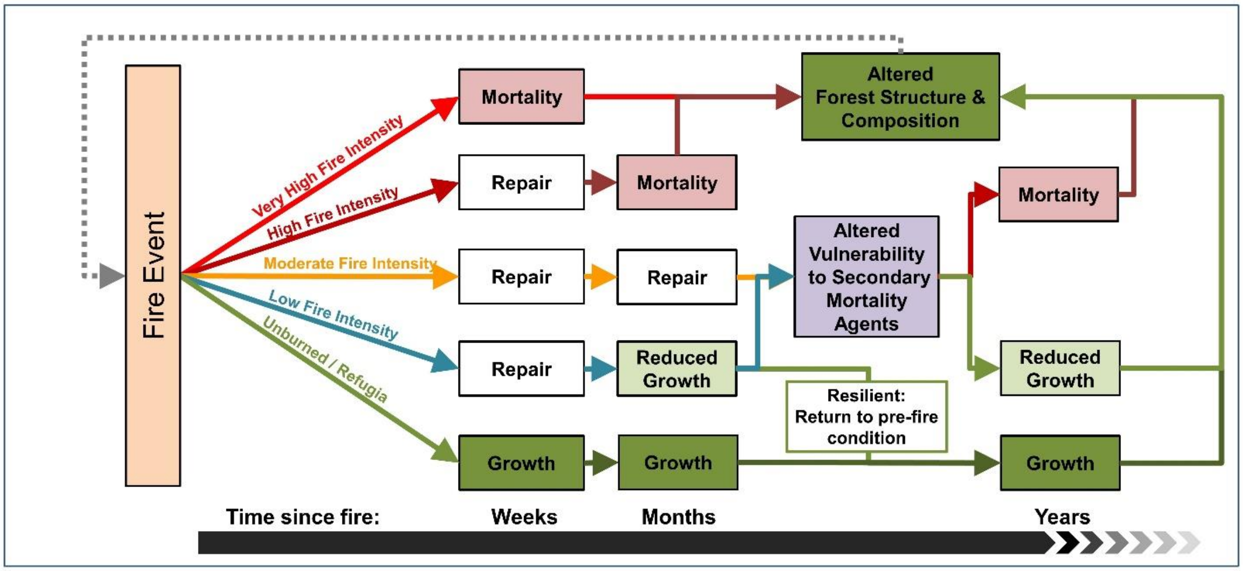

Figure 6. Conceptual framework for quantifying impacts of fire intensity on physiology, growth, and vulnerability of coniferous forests. In this conceptual system, several post-fire recovery pathways exist for trees or forests depending on the initial fire intensity. We hypothesize that higher intensity fires cause trees to incur more damage, which can lead to immediate or delayed mortality depending on tree resources available to repair physiological function. For any post-fire pathway, trees in better physiological condition or those exposed to fewer environmental stressors will likely experience a lower impact to post-fire growth and a lower probability of mortality. Source: Sparks et al. 2018.

Science Delivery Activities

The research described above has produced two peer-reviewed journal articles (plus one article in review) and a PhD Dissertation – see Table 1 and Appendix B for details. Additionally, results from the prescribed fire experiment will be presented in a Northern Rockies Fire Science Network research brief titled ‘Fire behavior and ecological effects resulting from burning masticated forest fuels’. This brief is expected to be published by Fall 2018.

Table 1. Project deliverable, description and delivery dates. Asterisks (*) indicate deliverables in original proposal.

Deliverable Type	**Description**	**Delivery Dates**
*Field Tour	University of Idaho Experimental Forest Field Day	August 2016
*Conference presentation	Presentation of work at American Geophysical Union Fall Meeting (poster)	December 2016
Refereed publication	Sparks AM, Smith AMS, Talhelm AF, Kolden CA, Yedinak KM, Johnson DM (2017) Impacts of fire radiative flux on mature *Pinus ponderosa* growth and vulnerability to secondary mortality agents, *International Journal of Wildland Fire* **26**, 95-106, doi:10.1072/WF16139.	January 2017

*Annual Report	Progress report sent to JFSP	August 2017
*Dissertation chapter	Cross-comparison of physical, spectral, and physiological post-fire tree response at the laboratory and stand scale	May 2017
Refereed publication	Sparks, A.M., Kolden, C.A., Smith, A.M., Boschetti, L., Johnson, D.M. and Cochrane, M.A., 2018. Fire intensity impacts on post-fire temperate coniferous forest net primary productivity. *Biogeosciences*, 15(4), p.1173.	February 2018
*Final Report	Final report on tasks and deliverables sent to JFSP	May 2018
Refereed publication	Sparks, A.M., A.F. Talhelm, R. Partelli Feltrin, A.M.S. Smith, D.M. Johnson, C.A. Kolden, L. Boschetti (in review), An experimental assessment of the impact of drought and fire on western larch mortality and recovery, *International Journal of Wildland Fire*, WF18044.	In review
Research Brief	Northern Rockies Fire Science Network research brief: 'Fire behavior and ecological effects resulting from burning masticated forest fuels'	Fall 2018 (expected)

Conclusions (Key Findings), Implications for Management, and Future Research

This work has implications for both land managers and researchers seeking to quantify and predict impacts of prescribed and wildland fires on large tree growth and vulnerability post-fire. Specifically, the resin duct results suggest that use of low-intensity, non-lethal prescribed fires could be applied to help increase ponderosa pine defenses and potentially reduce vulnerability to bark beetles. The stand-scale prescribed burn experiments also highlight the importance of quantifying fine-scale fire behavior (instead of average fire behavior for entire fire spatial extent and duration) for determining fire effects. Ultimately, the stand- and landscape-scale work provide a conceptual framework that researchers and managers could use for spatiotemporal post-fire recovery assessments.

One of the key growth areas in fire science is improving predictions of tree mortality and fire effects, including post-fire recovery of trees that live through the fire. Currently, fire mortality models and post-fire recovery models are relatively simplistic and not based on mechanistic processes; rather, they have been developed from empirical observations of individual tree mortality on the landscape. Thus, this work helps to inform development of more mechanistic and process-based mortality and effects models, particularly as those models are often used to make applied decisions regarding the use of prescribed fire or the use of resource management objective-focused wildfire (i.e., non-full suppression fires). There is also no current delineation of fire effects and post-fire recovery based on stratification of fire regimes, from fire-resilient to fire-susceptible. Such stratification is necessary to more accurately establish baseline post-fire recovery normal, in order to monitor departures from normal associated with climate change, forest management practices, bark beetle epidemics, or other forest change agents. This work informs future research in this arena of a need to stratify by fire regime type, rather than the ecoregion stratification approach that has been widely used.

It is clear from the differences between sapling and large tree dose-response studies that more research is needed to characterize large tree response to increasing fire intensity, and to determine whether laboratory results scale up to the landscape scale. This is particularly true because of the considerable difficulty of controlling for environmental variables in the field; the instrumented plots in the experimental Rx fires used in this work were selected to provide a range of different fire intensities but likely introduced micro-site environmental variation. As this environmental variation was not measured in this work, future studies should strive to control for these factors by burning trees in similar environmental conditions or by burning a very high number of plots to remove the effects of the environment across plots and isolate the variable of interest (e.g., fire intensity). Additionally, as very few trees died within our plots, a key facet of future work in this arena will be to utilize higher fire intensities to quantify heat doses associated with large tree mortality.

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Appendix A: Contact Information for Key Project Personnel

Crystal Kolden
Department of Forest, Rangeland, and Fire Sciences
University of Idaho
875 Perimeter Drive
Moscow, ID 83844
ckolden@uidaho.edu
208.885.6018

Aaron Sparks
Department of Forest, Rangeland, and Fire Sciences
University of Idaho
875 Perimeter Drive
Moscow, ID 83844
asparks@uidaho.edu

Appendix B: List of Completed Science Delivery Products

Journal Articles:

Sparks, A.M., Smith, A.M., Talhelm, A.F., Kolden, C.A., Yedinak, K.M. and Johnson, D.M., 2017. Impacts of fire radiative flux on mature *Pinus ponderosa* growth and vulnerability to secondary mortality agents. *International Journal of Wildland Fire*, 26(1), pp.95-106.

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Sparks, A.M., A.F. Talhelm, R. Partelli Feltrin, A.M.S. Smith, D.M. Johnson, C.A. Kolden, L. Boschetti (in review), An experimental assessment of the impact of drought and fire on western larch mortality and recovery, *International Journal of Wildland Fire*, WF18044.

PhD Dissertation:

Sparks, A.M., 2017. Development of a Spatial Severity Model for the Quantification of Wildland Fire Effects in Coniferous Forests (Doctoral dissertation, University of Idaho).

Technical Reports and Briefs:

Morgan, P., A.M.S. Smith, A.M. Sparks, C. Stevens-Rumann, Z. Lyon, R. Keefe (in press), Fire behavior and ecological effects resulting from burning masticated forest fuels, Northern Rockies Fire Science Network.