FINAL REPORT

Title: How vegetation recovery and fuel conditions in past fires influences fuels and future fire management in five western U.S. ecosystems

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Abbreviations/Acronyms

CWD	Coarse Woody Debris
dNBR	Differenced Normalized Burn Ratio
FWD	Fine Woody Debris
IDH	Intermediate Disturbance Hypothesis
LandTrendr	Landsat Trends in Disturbance and Recovery
MRPP	Multi-Response Permutation Procedure
MTBS	Monitoring Trends in Burn Severity
NMDS	Non-metric Multi-Dimensional Scaling
RF	Random Forests
WUI	Wildland-Urban Interface

Keywords

burn severity, fire effects, fuel accumulation, remote sensing, vegetation recovery

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Figure 0. View of the South Fork Salmon River drainage burned in the 2007 East Zone Complex, south of Warren, ID on 12 June 2018.

Abstract

Mixed severity wildfires burn large areas in western North America forest ecosystems in most years and this is expected to continue or increase with climate change. Little is understood about vegetation recovery and changing fuel conditions more than a decade post-fire because it exceeds the duration of most studies of fire effects. We measured plant species composition, conifer seedling regeneration, fuel loads, and ground cover at 15 wildfires that burned 9-15 years previous in five western U.S. vegetation types distributed across eight states including Alaska. The 15 fires were selected for having been previously sampled immediately post-fire and re-sampled one year later, thus providing a re-measurement opportunity for a more powerful analysis of long-term vegetation recovery. These existing field sites were used to partially populate a new stratification of the post-fire landscapes based on one-year burn severity classifications by the Monitoring Trends in Burn Severity (MTBS) Project, elevation, and transformed aspect; additional new sites were then added to fill the stratification, such that our stratified random sampling design was balanced.

In the northern Rockies, plant species diversity a decade post-fire is highest on moderate burn severity conditions, and total fuel load appears to peak in the decade that follows. In dry ponderosa pine forests, burn severity was not as influential on understory plant species composition and cover as climate, particularly precipitation. Seedling regeneration is more affected by distance from seed sources than by burn severity. Across all 5 vegetation types and 14 of the wildfires sampled, we found that vegetation cover, composition, and seedling regeneration 9-15 years post-fire is remarkably resistant to high severity fire effects. The 2002 Hayman Fire in Colorado, where burn severity was extreme, appears to be an exception.

From our suite of field measurements, percent vegetation cover most strongly determines Landsat pixel reflectance. We related overstory and understory cover estimates to remotely sensed trajectories of vegetation recovery, as indicated by annual time series of Normalized Burn Ratio (NBR) extracted from Landsat satellite image time series using the Landsat Trends in Disturbance and Recovery (LandTrendr) algorithm. NBR trajectories provided consistent information on initial burn severity, recovery rate, and percent recovered to pre-fire conditions, which varied by burn severity class from 75% (low) to 60% (moderate) to 48% (high).

We hosted a workshop at the University of Idaho’s McCall Outdoor Science School (MOSS) to share results regarding long-term post-fire vegetation recovery with managers. At the workshop, we also partnered with another FY14 JFSP project (14-1-02-03) that modeled reburn potential. Researchers and managers discussed the implications of long-term vegetation recovery, fuel accumulation, and reburn potential for both fuels and fire management, both in the classroom and on the associated field tour.

We fully funded two graduate students (PhD and MS) and partially funded four other Masters students, all of whom focused their degrees on fire ecology. All of their thesis work has been presented at national professional conferences, and publications of their work are either in review or in preparation. We intend to archive all data collected in the Forest Service Research & Development permanent data archive to promote their broader use.

I. Objectives

Our proposal was responsive to Task 2 of the FY14 FON, “Influence of past wildfires on wildfire behavior, effects and management.” Our five objectives, copied as proposed, were:

- ✓ Quantify surface and canopy fuel loads 7-15 years postfire across the full range of burn severities in five vegetation types. *This objective was met.*
- ✓ Survey plant cover, native species recovery, exotic species establishment, and seedling densities across the same sample sites as above as metrics of ecosystem recovery. *This objective was met.*
- ✓ Relate field plot measures to LandTrendr image products to assess landscape-level implications of large fires on fuel loads, effectiveness as fuel treatments, vegetation cover, and plant community composition as measures of ecosystem recovery across 15 wildfires and five vegetation types. *This objective was met.*
- ✓ Produce maps of recovery rates for fuels and vegetation conditioned on recent fire history, vegetation type, burn severity and geographic location. *This objective was met.*
- ✓ Hold a workshop and webinars with fuel and fire managers regarding how post-fire fuel and vegetation trajectories influence fuel and fire management options, focused on effectiveness in limiting fire extent and burn severity of subsequent fires and furthering vegetation management goals. *This objective was met.*

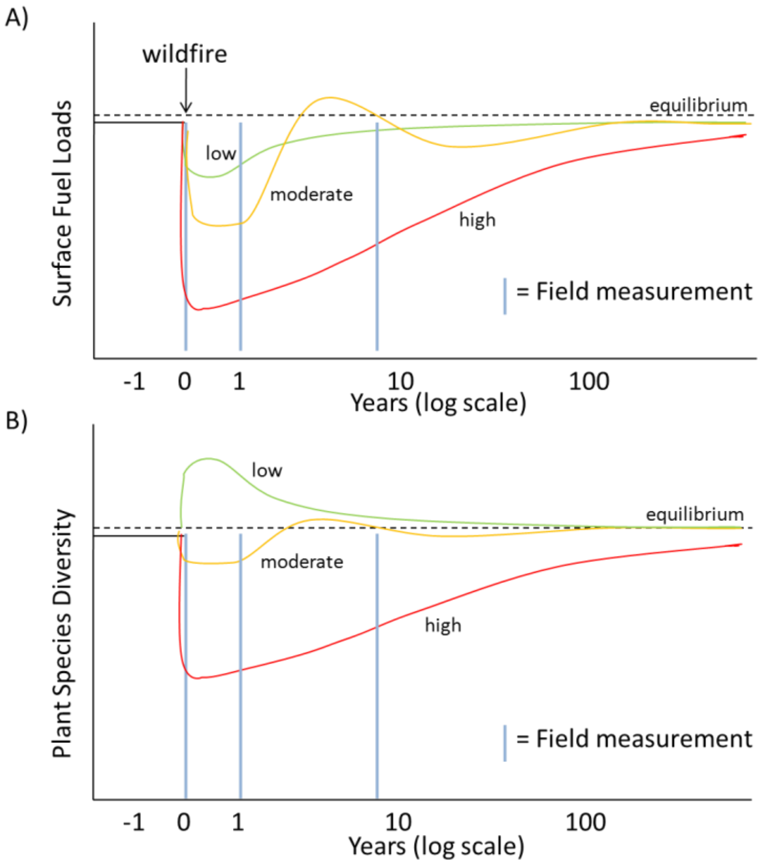

Figure 1. Hypothetical responses of surface fuel loads and plant species diversity as a function of low, moderate or high burn severity. Year 0 marks the time of the wildfire, which we proposed to consider as a surrogate for fuel treatment.

Our working hypotheses were:

1. Surface fuel accumulation will be highest and fuel treatment effectiveness lowest following moderate severity burns where most but not all of the overstory trees are killed and fine canopy fuels are not consumed (Fig. 1A).
2. Vegetation recovery (e.g., species diversity) to pre-fire levels will be slowest in large, severe fire patches (Fig. 1B).
3. Considering recent wildfires as fuel treatments, conditioned on vegetation type and burn severity, can be formalized as a cost-effective fuel and fire management strategy.

II. Background

Many large fires have occurred in recent decades across the western US and projections predict this trend to continue (Littell et al. 2009) along with generally warmer and drier conditions. Extensive areas have and will burn severely (more than 70% overstory mortality) (Miller et al. 2009). Accurate estimates of fuel conditions and vegetation recovery rates of various ecosystems with time since the last burn would assist fuel and fire management decisions. Understanding vegetation response trajectories based upon burn severity and other post-burn indicators will increase our ability to effectively prioritize management options to address long-term fuel and fire management objectives.

Burn severity describes the ecological change that results from a fire (Lentile et al. 2006, Keeley 2009). The differenced Normalized Burn Ratio (dNBR) is a widely used indicator of burn severity (Key and Benson 2006). Mapping burn severity from satellite imagery allows rapid, consistent evaluation across large areas. These satellite image-derived indices of the relative change in vegetation conditions between pre- and post-fire scenes (Smith et al. 2007; Lentile et al. 2006, 2009, Hudak et al. 2007) have been related to one-year post-fire vegetation cover in many studies. Although first-year responses to fire are informative, longer term responses (up to 20 years post-burn) are likely more important for assessing ecosystem resilience to fire and implications for managers.

The free availability of the entire Landsat image archive has stimulated development of powerful image time series analysis techniques such as Landsat Trends in Disturbance and Recovery (LandTrendr) to map multiple disturbances and post-disturbance vegetation recovery. Additionally, larger fire disturbances have been mapped nationwide by the Monitoring Trends in Burn Severity (MTBS) project (Eidenshink et al. 2007). Quantifying post-fire vegetation recovery rates to pre-fire conditions as we propose is important if we are to plan effective strategies for fuel and fire management of complex landscapes.

Hypothetical trajectories of ecosystem recovery in response to burn severity (Figure 1) can be constructed based on severe fires in boreal (Hicke et al. 2003) and lodgepole pine forest ecosystems (Kashian et al. 2006, Turner et al. 2010). Severe fire reduces not only fuel loads available for subsequent fires but also understory plant cover and diversity (Lentile et al. 2007) and tree regeneration. The time required for recovery of these and other metrics of ecosystem condition of interest to land managers differs between different vegetation types but are poorly quantified. Longer-term field measures are needed to better understand these ecological trajectories. Links to remotely sensed data are needed to upscale these measures to the landscape level where fuel and fire management decisions are made.

We sampled post-fire fuel and vegetation across the full range of burn severities, as quantified by MTBS, across five fire-adapted ecosystems in the western U.S. including Alaska. Past wildfires selected for field sampling occurred 9-15 years prior (Table 1). Decomposing snags are currently falling at rapid rates (Mitchell and Preisler 1998) to alter fuel loading conditions and reburn potential (Teske et al. 2012). We linked these field measures of fuel and vegetation with map products generated from analysis of 1984-2016 Landsat image time series processed through LandTrendr to infer vegetation recovery rates at the landscape level.

III. Materials and Methods

3.1 Study area descriptions and locations

We sampled as many past wildfires in the field as we had proposed (n=15; Table 1, Fig. 2), on as many vegetation types as proposed (n=5; ponderosa pine, dry mixed conifer, moist mixed conifer, conifer/oak/chaparral, subarctic boreal spruce), and accomplished this safely, with no lost time injuries.

Table 1. Eight states where wildfires were sampled, listed chronologically in the order of sampling. Burn year is shown in parentheses.

2013-15: Montana (2003): Black Mountain 2, Cooney Ridge, Robert and Wedge Canyon
2015: California (2003): Simi, Old/Grand Prix
2015: Colorado (2002): Hayman
2015: South Dakota (2000): Jasper
2015: Washington (2005): School
2016: Oregon (2007): Egley
2016: Idaho (2007): Cascade, East Zone
2016: Alaska (2004): Porcupine, Chicken, Wall Street

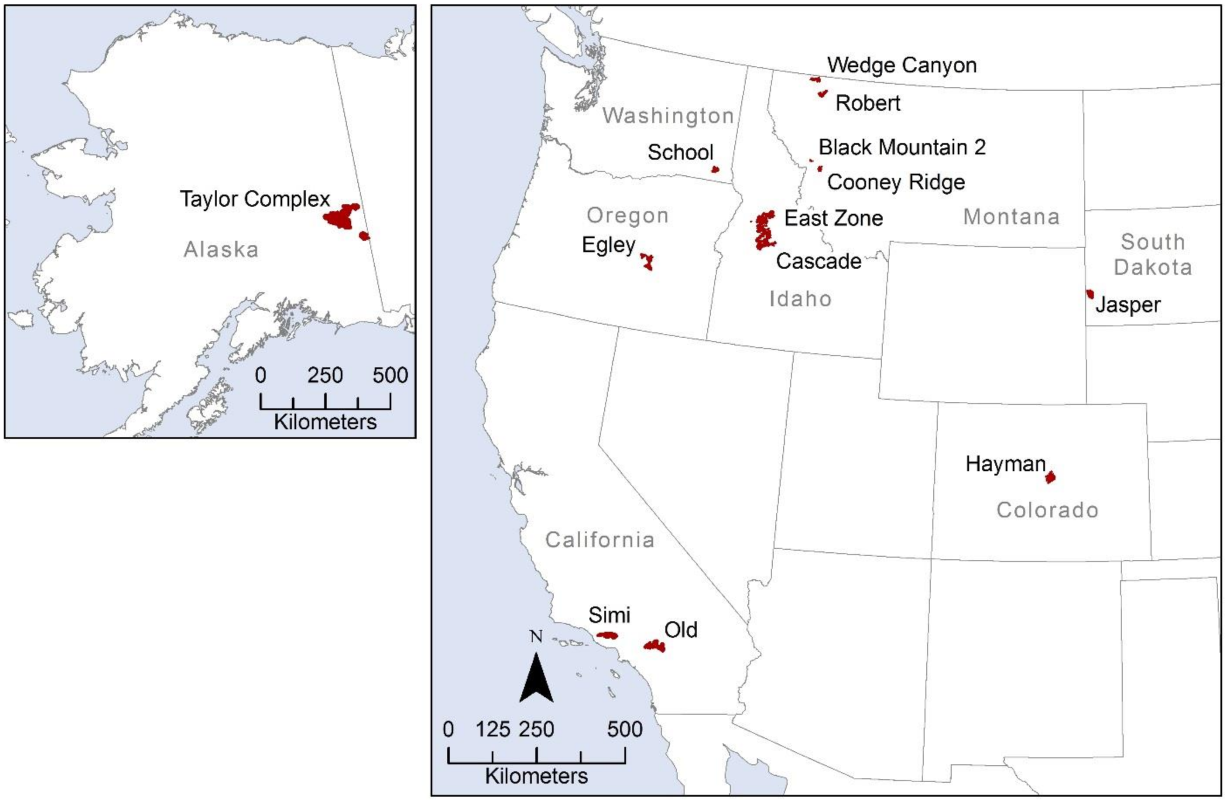

Figure 2. Wildfires (n=15) sampled in the long-term vegetation recovery (VegTrek) project.

As proposed, field site selection was based on a stratified random sampling design based on elevation, aspect (transformed), and one-year post-fire dNBR burn severity as classified by MTBS (Fig. 3).

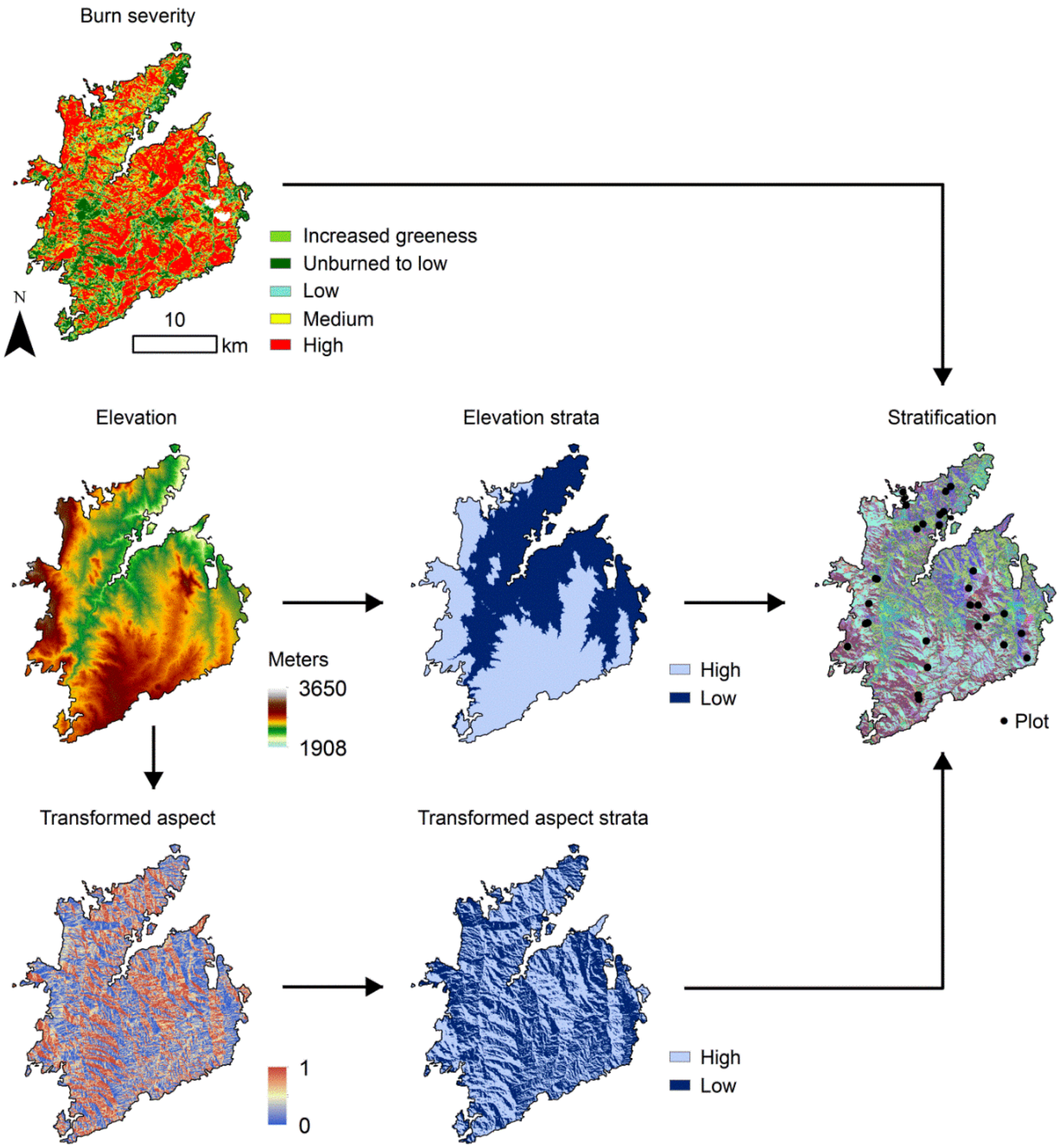

Figure 3. Example of stratification for field sampling (2002 Hayman fire shown).

The landscape stratification ensured that the field sites represented the full range of variability in both burn severity and environmental gradients as determined by topography. Placing field sites randomly within strata ensured that our sampling of the burn area was unbiased. As proposed, we conducted each stratification by vegetation type within a specific geographic locale, and not necessarily by each individual wildfire. In other words, two wildfires burning in close proximity within the same vegetation type were treated (in terms of sampling) as a single wildfire event. Namely, these were: Black Mountain 2 and Cooney Ridge, Robert and Wedge Canyon, East Zone and Cascade, and the 3 Alaska fires that comprised the Taylor Complex (Fig. 2, Table 2).

As proposed, we exploited the opportunity to re-measure old field sites established in past rapid response research projects, provided we could safely access them. Old field sites partially populated our landscape stratifications; to fully populate the strata, new field sites were subsequently added at random locations yet close enough to navigable roads to permit practical access. Including the older field data was important to empower analyses of long-term vegetation recovery (Table 2).

In the summer 2015 field season, we began adding unburned sites to our stratification and sampling. This increased the number of new sampling sites by 25% compared to our proposal to sample only low, moderate, and high burn severities. Given the long time that has transpired since these fires, we decided it was important to compare our site recovery data to sites in nearby unburned areas. The unburned sites thus provided context, and a benchmark against which to compare recovery metrics, especially the diversity metrics which were derived solely from field data, but also the satellite data in order to relate vegetation cover recovery trajectories to unburned conditions in time (pre-fire conditions) and space (unburned sites).

Table 2. Number of field sites sampled by our project, with number of old field sites re-measured shown in parentheses. Burn severity strata were determined by MTBS, nominally based on 1-year post-fire imagery. Old field sites were established during rapid response research projects prior to MTBS availability. Ground calls of burn severity class in the initial assessments often differed from MTBS.

Wildfire(s) Stratified	High	Moderate	Low	Unburned	Total
Black Mountain 2, Cooney Ridge	4 (2)	4 (1)	8 (8)	4 (0)	20 (11)
Robert, Wedge Canyon	5 (3)	6 (3)	7 (5)	4 (0)	22 (11)
Simi, Old/Grand Prix[1]	3 (3)	5 (4)	6 (5)	0 (0)	14 (12)
Hayman	4 (2)	4 (1)	7 (4)	4 (0)	19 (7)
Jasper	4 (4)	4 (4)	4 (4)	4 (4)	16 (16)
School	4 (3)	4 (4)	4 (3)	4 (1)	16 (11)
Egley[2]	16 (16)	22 (21)	26 (25)	13 (8)	77 (70)
Cascade, East Zone	8 (2)	8 (2)	8 (1)	8 (0)	32 (5)
Porcupine, Chicken, Wall Street	8 (3)	8 (6)	8 (5)	8 (1)	32 (15)
All Fires	56 (38)	65 (46)	78 (60)	49 (14)	248 (158)

[1] We added unburned sites to the stratification after these California wildfires had been sampled.
[2] Existing sites (n=70) were treated (n=35) and untreated (n=35) pairs designed to test fuel treatment effectiveness. Only untreated sites were considered in the stratification for 2016 sampling, but treated sites were also re-measured in 2016 for their value in assessing long-term fuel treatment effectiveness.

3.2 Field Measurements

At all field sites, we measured fuel loads, vegetation cover, plant species composition, and tree regeneration. Understory vegetation cover was ocularly estimated by plant species and functional type, within a 1 m x 1 m square microplot situated at the center of each field site and as well as four peripheral plots 30 m away in orthogonal directions oriented with the prevailing aspect (Fig. 4, Hudak et al. 2011). Ground cover fractions of surface materials (green and non-photosynthetic vegetation, litter, mineral soil and rock) were ocularly estimated in the same five spatially distributed plots per site, and overstory canopy closure was measured four times per nested plot using a spherical densiometer. We also measured litter and duff depths at each plot, and ocularly estimated fine woody surface fuel loads (1hr, 10hr, 100hr) following the photoload sampling

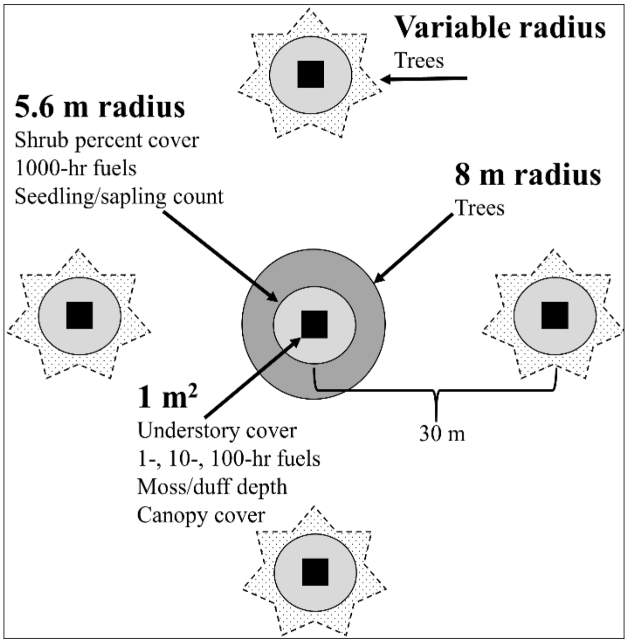

Figure 4. Field site nested plot layout (not to scale) showing central plot and four peripheral plots, along with the components measured within each plot. Tall shrub percent cover was measured only at the center plot. The variable radius plot was based on a 2 m^2 ha^{-1} BAF prism.

technique developed by Keane and Dickinson (2007). Within a 0.02 ha (8 m radius) plot at the center of each field site, tree species, status, diameter at breast height (dbh), height, and height to live crown were tallied (Hudak et al. 2007, Hudak et al. 2011). Tree species, status, dbh, basal area and density was also measured within a variable radius plot centered over each of the four peripheral plots, centered over each of the five 1 m^2 microplots. Seedlings and saplings were tallied within a concentric 0.01 ha (5.6 m radius) subplot, also centered over each of the five 1 m^2 microplots. On a sample of conifer seedlings, annual nodes were tallied and height growth between the nodes was measured. Within the site center 0.01 ha subplot, tall shrub cover was ocularly estimated, and coarse woody surface fuel load (1000hr) was estimated per Keane and Dickinson (2007). Each of the five nested plots per field site was accurately geo-located with a Trimble GPS with differential correction. Like existing field sites, the center plot of new field sites was monumented with rebar to facilitate future re-measurement opportunities.

3.3 Remote Sensing

The NBR data used in this study were derived from the LandTrendr spectral-temporal segmentation algorithm. LandTrendr identifies breakpoints (referred to as vertices) in an image pixel time series between periods of relatively consistent spectral trajectory. From these breakpoints, a new time series is constructed, where each annual observation is interpolated to fit on a line segment between vertices (Figure 3). The result is an idealized, trajectory-based, time series free from noise, where each observation is placed in the context of a spectral-temporal trend. We chose this fitted data format over unaltered surface reflectance to reduce the influence of noise in the calculation of post-fire percent NBR recovery, and to place the recovery in terms of a point along a trajectory.

Fitted NBR data were produced using the Google Earth Engine (Gorelick et al. 2017) implementation of LandTrendr (Kennedy et al. 2018). For each region, we assembled a collection of USGS surface reflectance images (Masek et al. 2006, Vermote et al. 2016) from 1984 to 2016, for dates June 1st through September 30th. The collection included images from

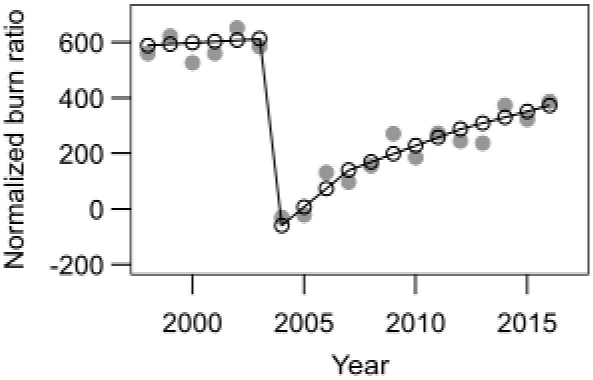

Figure 5. The NBR data used in this study were derived from the LandTrendr spectral-temporal segmentation algorithm. LandTrendr identifies breakpoints (referred to as vertices) in an image pixel time series between periods of relatively consistent spectral trajectories that combine to reveal the dominant, underlying spectral history of a pixel.

TM, ETM+, and OLI sensors. Each image in the collection was masked to exclude clouds and cloud shadows using the CFMASK algorithm (Zhu et al. 2015), which is provided with the surface reflectance product. Additionally, OLI image bands 2, 3, 4, 5, 6 and 7 were transformed to the spectral properties of ETM+ bands 1, 2, 3, 4, 5 and 7, respectively, using slopes and intercepts from reduced major axis regressions reported in Table 2 of Roy et al. (2016).

Transforming OLI data to match ETM+ data permitted inter-sensor compositing to reduce multiple observations per year to a single annual spectral value, which is a requirement of the LandTrendr algorithm. To calculate composites, we used a medoid approach: For a given image pixel, the medoid is the value for a given band that is numerically closest to the median of all corresponding pixels among images considered. Medoid compositing was performed for each year in the collection and included images from any sensor contributing to the annual set of summer-season observations for the year being processed. The result was a single multi-band image, per year, free of clouds and cloud shadows, and represents median summer-season surface reflectance. From these annual medoid composites, NBR was calculated and provided as the time series input to the LandTrendr algorithm, whose parameters were set according to Table 2 of Kennedy et al. (2012). The result from LandTrendr was an annual time series of NBR fitted to vertices of spectral-temporal segmentation.

IV. Results and Discussion

Two already published refereed journal articles reporting results that were partially funded from this project are summarized in the first subsection below. Results from another eight papers either in review or preparation, summarized in the subsequent subsections, were presented at a special session on “Long-term Vegetation Recovery in Five Western Ecosystems” that PI Andrew Hudak organized at the Association for Fire Ecologists (AFE) Congress in November 2017 in Orlando, FL. The eight papers are either in review or preparation for a special issue of *Fire Ecology* to be entitled “Frontiers in Fire Ecology.”

4.1 Indicators of burn severity at extended temporal scales: A decade of ecosystem response in mixed conifer forests of western Montana (Lewis et al. 2017, Hudak et al. 2017).

We collected field and remotely sensed data spanning 10 years after three 2003 Montana wildfires to monitor ecological change across multiple temporal and spatial scales. Multiple endmember spectral mixture analysis was used to create post-fire maps of: char, soil, green vegetation (GV) and non-photosynthetic vegetation (NPV) from high-resolution 2003 hyperspectral (HS) and 2007 QuickBird (QB) imagery, and from Landsat 5 and 8 imagery collected on anniversary dates in 2002, 2003 (post fire), 2004, 2007 and 2013. Initial estimates of char and NPV from the HS images were significantly correlated with their ground-measured counterparts (ρ = 0.60 (P = 0.03) and 0.68 (P = 0.01) respectively), whereas HS GV and Landsat GV were correlated with canopy GV (ρ = 0.75 and 0.70 (P = 0.003) respectively). HS imagery had stronger direct correlations with all classes of fine-scale ground data than Landsat and also had stronger predictive correlations with 10-year canopy data (ρ = 0.65 (P = 0.02) to 0.84 (P = 0.0003)). There was less than 5% understorey GV cover on the sites initially, but by 2013, it had increased to nearly 60% regardless of initial condition (Fig. 6). The data suggest it took twice as long for understorey GV and NPV to replace char and soil as primary ground cover components on the high burn severity sites compared to other sites.

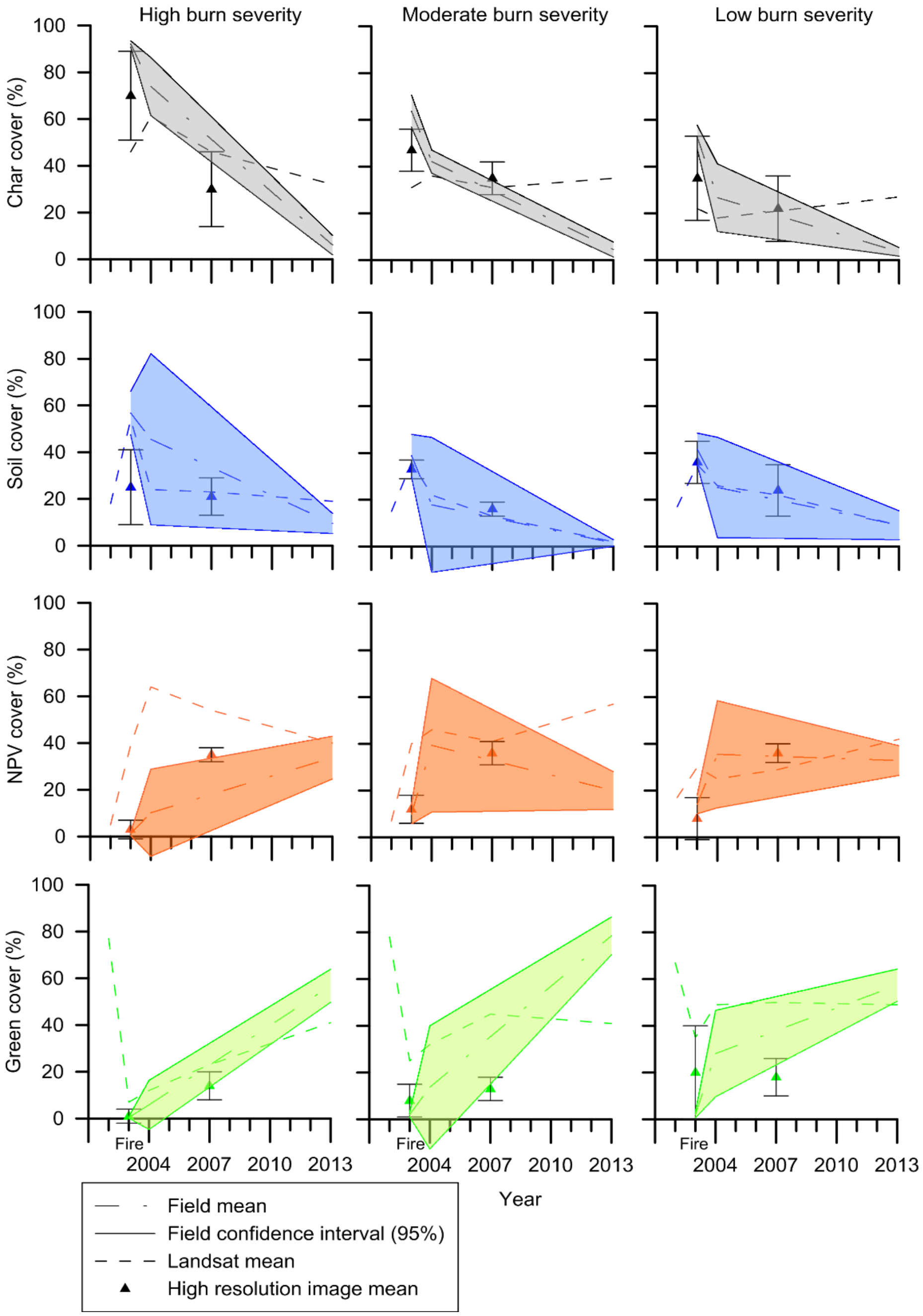

Figure 6. Field site characteristics visually compared with 2002–04 and 2007 Landsat 5, 2013 Landsat 8, 2003 hyperspectral and 2007 QuickBird fractional cover image estimates. A 95% confidence interval is shaded around the field means (understory ground cover) to illustrate how well the image estimates compare with the range of variability measured in the field. (GV, green vegetation; NPV, non-photosynthetic vegetation.)

One of the revisited Montana field sites merits additional discussion, as it was much more intensively studied spatially and temporally than any other field sites associated with this entire project. It was the site of a burnout operation conducted by researchers and managers on 3 September 2003 just outside the perimeter of the ongoing 2003 Cooney Ridge Fire. Since it was a planned burnout, it was a unique site in that pre-fire fuels were measured in a single plot on the day of the burnout (Fig. 7a), followed by active fire measurements (Fig. 7b) of fire radiative heat release, post-fire fuels the next day (Fig. 7c), fire effects on vegetation and soils later that same month, 1-year post-fire vegetation effects in July 2004, and finally, on 13 August 2013, 10-year post-fire measurements to assess long-term vegetation recovery. By that time the majority of snags had fallen, reducing canopy closure by ~33% and increasing forest floor fuel loads, especially of the large 1000 hr and 100 hr fractions. The burnout experiment caused fire effects that ranged from low severity to high severity depending on the plot, and typical of other field sites we observed in western Montana. The fire reduced green vegetation cover and plant species richness to zero. Species richness a year later was 5.5 species m^{-2}, which increased to 12.5 species m^{-2} in 2013. The fuel plot, perhaps because it was at the base of the hillslope, had the highest diversity of any of the nested field plots at the site; species richness there increased from 9.4 species m^{-2} in 2004 to 15.6 species m^{-2} in 2013. Tree seedling density increased six-fold, from 0.16 seedlings m^{-2} in 2004 to 1.0 seedlings m^{-2} in 2013.

Figure 7. View of the fuel plot at the site of a burnout operation on the Cooney Ridge Fire, a) before, b) during, and c) after the fire. The plot burned at moderate severity. Fuel consumption was 5.4 kg m^{-2}.

4.2 Understory plant community response along a burn severity gradient ten years post-fire in mixed conifer forest of the intermountain western USA

Authors: Eva K. Strand, Kevin L. Satterberg, Andrew T. Hudak, John C. Byrne, Alistair M.S. Smith

Wildfire is an important ecological process within the mixed conifer forests of the western United States. Scientists and land managers are currently concerned because wildfires have increased in frequency and size over recent decades and these trends are expected to continue under a warming climate. Assessments of burn severity enable managers to assess impacts of fires on ecosystem goods and services, however, long term (> 10 years) assessments of plant community composition and structure at a variety of burn severity levels is largely unexplored. Evaluating understory response to fire will become increasingly important as increased wildfire activity will result in larger land areas in early successional stages and young forest. Forest understory will be particularly important in areas where establishment and growth of trees will become limited due to warmer climate conditions. This study compares a satellite-sensor based index of burn severity (dNBR) at seven wildfires from the 2003-2007 fire seasons in western Montana, central Idaho and eastern Washington to field measurements including tree cover, green understory cover, and understory species diversity and composition. We evaluated species diversity and richness along a dNBR gradient using an ordinary least-squares regression with a polynomial term. Ordination techniques and a non-parametric multi response permutation procedure (MRPP) was used to evaluate the species composition along burn severity, canopy cover, climate, and topographic gradients. We further analyzed species functional traits (lifeform, lifecycle, origin, fire response, and shade tolerance) and evaluated indicator species by burn severity class.

Species diversity and richness showed a nonlinear relationship with the remotely sensed burn severity index dNBR, with a maximum observed at moderate burns severity levels (Fig. 8) supporting the application of the Intermediate Disturbance Hypothesis (IDH) for burn severity. Overall, both beta and gamma diversity was higher in low and moderately burned sites compared to high severity or areas that did not burn in these fires. Multivariate analysis of the large species datsets show strong overlap in species composition between severity level but lower dispersion between sites burned at high severity, indicating that those areas are still recovering 9-10 years post-fire. Functional trait analysis revealed lower shrub cover and higher grass and forb cover in high severity burns, higher cover of tree seedlings in burned areas compared to unburned, and more shade tolerant species in unburned areas (Figure new). A higher proportion of residual colonizers was observed in burned areas compared to unburned, for example snowbrush ceanothus (*Ceanothus velutinus*) and lodgepole pine (*Pinus contorta*). Indicator species analysis computed indicator values (IV) and identified species indicative of the burn severity levels in the large species dataset. Wild strawberry (*Fragaria virginiana*; IV= 28.5, *P* = 0.024), hawkweed (*Hieracium* spp.; IV = 25.4, *P*=0.024), Sitka valerian (*Valeriana sitchensis*; IV = 16.7, *P*=0.018) and starry Solomon's seal (*Smilacina stellata*; IV = 15.3, *P* = 0.045) were identified as indicator species for low severity sites. Western larch (*Larix occidentalis*; IV=21.0; *P*=0.023) was identified for moderate severity sites. Fireweed (*Chamerion angustifolium*; IV = 39.2, *P* = 0.006), common dandelion (*Taraxacum officiale*; IV= 24.9, *P*=0.017), and snowbrush (*Ceanothus velutinus*; IV = 15.0, P = 0.026) were identified as indicators for high severity sites. Indicator species identified in areas that did not burn in the sampled fires were lichen species (IV = 30.9, *P* = 0.039), sidebells wintergreen (*Orthilia secunda*; IV = 23.5, *P* < 0.001), and rattlesnake plantain (*Goodyera oblongifolia*; IV = 19.7, *P* = 0.013). Introduced species were present at low cover levels within the studied fires. Introduced annual grasses were observed at low levels on 13 of the lower elevation sites (900-1500 m) with mean values ranging from 0.1-1.2% across burn severity classes, with one low severity site as high as 12% cheatgrass (*Bromus tectorum*) cover. Annual grass species were dominated by cheatgrass but also included field brome (*Bromus arvensis*) and rattlesnake brome (*Bromus briziformis*). Annual grasses were basically absent on higher elevation sites (> 1500 m) except for one low severity site with 0.2% cheatgrass. The relatively recently introduced wiregrass (*Ventenata dubia* occurred on three sites on the School fire in Washington state. Common introduced perennial grasses, introduced as pasture grasses to North America, were Kentucky bluegrass (*Poa pratensis*), orchardgrass (*Dactylus glomerata*), and timothy (*Phleum pretense*).

Noxious weeds observed on sampled sites included spotted knapweed (*Centaurea stoebe*) which occurred on eight sites across burn severity levels; introduced thistle species were observed on

12 sites at cover levels at or below 6% and included Canada thistle (*Cirsium arvense*), and bull thistle (*Cirsium vulgare*). Observed introduced annual forbs were mouse-ear chickweed (*Cerastium sp*.), yellow lucerne (*Medicago falcate*), starwort (*Stellaria* spp.) and introduced perennial forbs included bird's-foot trefoil (*Lotus corniculatus*), common sheep sorrel (*Rumex acetosella*), common dandelion (*Taraxacum officiale)*, common mullen (*Verbascum thapsus*), common plantain (*Plantago major*), clover (*Trifolium* spp.), oxeye daisy (*Leucanthemum vulgare*), prickly lettuce (*Lactuca seriola*), yellow salsify (*Tragopogon dubious*), and veronica (*Veronica* spp.). Introduced shrubs occurring on three sites, included red raspberry (*Rubus idaeus*) and cutleaf blackberry (*Rubus laciniatus*).

Under current climate conditions, we conclude that the understory plant community was not fundamentally altered by fire and that wildfire in these mixed conifer forests of the intermountain western US contribute to increased species diversity both locally (alpha diversity) and at a regional level (gamma diversity). However, high severity burns take longer to recover and still, 9-10 years post-fire, show lower understory diversity compared to areas burned at lower severity. Our data indicate that increased fire activity in the forest will likely lead to larger proportions of residual colonizers and shade-intolerant grasses and forbs. Although our data only showed a low occurrence of invasive forbs and annual grasses, potential management challenges resulting from increased fire activity, particularly in the dry end of the mixed conifer forest, will likely continue to be increases in annual flammable grasses and invasive forbs. We concur with other researchers stating that frequent reburns or otherwise altered fire regimes could affect future forest structure, diversity and composition in the future.

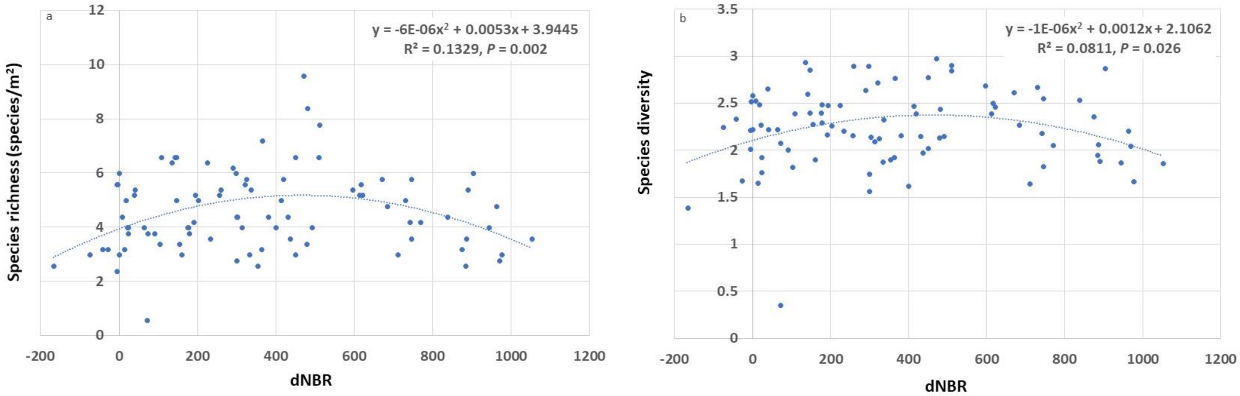

Fig. 8. Species richness (A) and Shannon's diversity index (B) as a function of the remotely sensed burn severity index (dNBR). The highest species richness and diversity are observed at moderate levels of dNBR. These results support the Intermediate Disturbance Hypothesis.

4.3 Fuel dynamics following wildfire in the US Northern Rockies forests

Authors: Stevens-Rumann, C., A.T. Hudak, P. Morgan and A. Arnold

Accumulation of dead woody material is a critical management concern following wildfires, especially given the possibility of subsequent wildfires. Moreover, this dead woody material also provides important ecological functions for forested ecosystems. Understanding when surface fuels are highest following wildfires and how these dynamics change after repeated fires affords land management agencies opportunities to adjust fuel reduction strategies without removing large quantities of dead trees that are important in these post-fire landscapes for a variety of ecosystem properties including wildlife, water and nutrient retention and soil stabilization. Here we examined seven different years-since-fire (1-24 years) across twelve wildfires in the northern Rockies to look at how woody surface fuels and standing dead trees change over time. Large diameter woody fuels peaked around 14 years post-fire while smaller woody fuels peaked at 20 years post-fire (Fig. 9). Fuel loads on repeated fires had a >40% fuel reduction. Surface fuel loads exceeded desired level in high burn severity sites but were within many desired ranges at low to moderate burn severity sites. Snag density across all size classes generally declined after 7-9 years, but large diameter snags were still present 24 years post-fire. Repeated fires resulted in >40% reduction in both surface fuels and standing trees compared to once burned areas at the same years-since-fire. Burned landscapes can serve a great ecological benefit by providing an infusion of both standing and downed dead woody material. These ecological considerations should be weighed against concerns about reburning potential and fire fighter hazards.

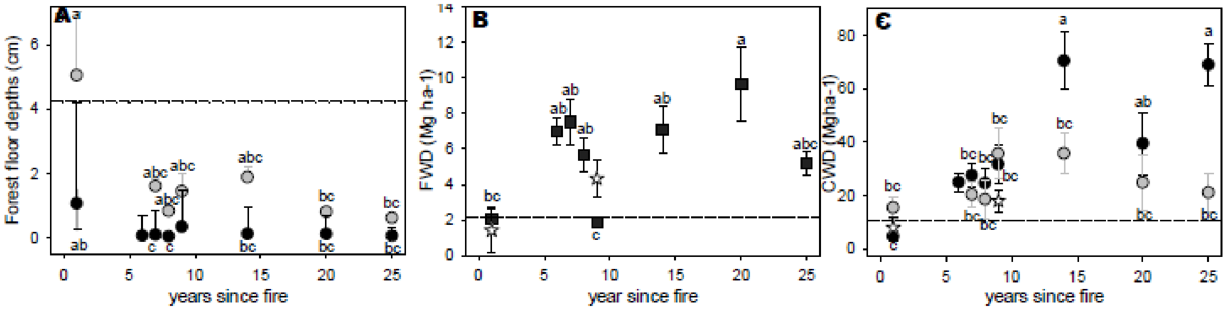

Figure 9. Effect of years since fire on A) Forest floor depth, B) FWD, and D) CWD loadings. Points indicate means for each year since fire with the standard error bars around each. Gray circles indicates lower burn severity means, black circles indicates high burn severity means, and black squares are means across both burn severities. Letters indicate significant differences from Tukeys HSD pairwise comparisons. Dashed line indicates means for unburned sites.

4.4 Long-term vegetation response following post-fire straw mulching

Authors: Bontrager, J.D., P. Morgan, A.T. Hudak, P.R. Robichaud (MS thesis chapter)

Mulching is one of the most common treatments applied immediately post-fire to reduce soil erosion potential and mitigate post-fire effects on water quality, downstream property and infrastructure, but little is known about the long-term effects (over 10 years) on vegetation response. We sampled six fires that were mulched between nine and 13 years ago. We compared understory plant species diversity and abundance, tree seedling density and height by species, and fractional ground cover on mulched and unmulched paired plots.

Mulch did not influence understory plant diversity, species richness, or fractional ground cover. However, on mulched plots, tree seedlings grew taller faster, especially on north-facing aspects, and there was 2% more graminoid cover. Mulch did not affect overall tree seedling density, but there were fewer ponderosa pine and more Douglas-fir in mulched areas, especially on south-facing slopes (Fig. 10).

Managers will be able to weigh the long-term implications of mulching against the short-term reductions in soil erosion potential. While there are many concerns about vegetation suppression and exotic species introduction from using straw mulch, our study suggests the long-term effects are subtle nine to 13 years after post-fire mulching.

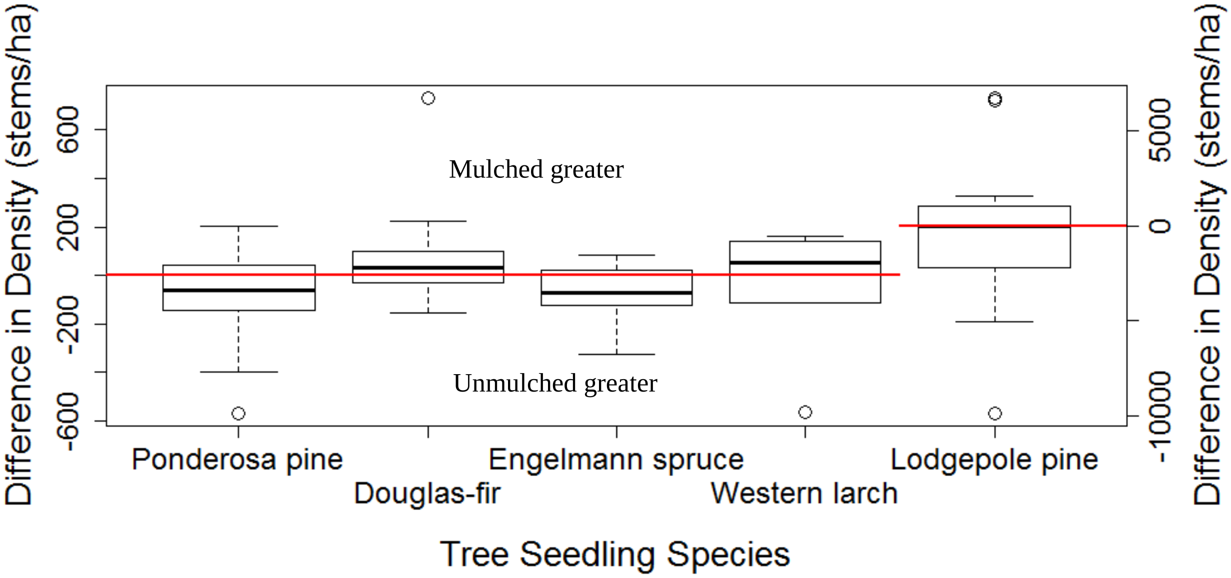

Figure 10. Differences in tree seedling density (stems ha^{-1}) by species calculated as unmulched density subtracted from mulched density. Any point above the zero line represents a higher value on the mulched plot, while any value below is a higher value on the unmulched plot of the pair. Only plot pairs with non-zero values were included. Note scale difference for lodgepole pine. For box plots, the thick line represents median (50% quantile), top and bottom of box are 75% quantiles and 25% quantiles respectively. Ends of whiskers extend a maximum of 1.5 times the median to 75% quantile or 25% quantile, or to the farthest point within that range, whichever is closest to the median. Circles are outliers beyond this range.

4.5 Effectiveness of fuel treatments tested by wildfire in ponderosa pine forest

Authors: Jessie M. Dodge, Eva K. Strand, Andrew T. Hudak, Benjamin C. Bright, Darcy H. Hammond (MS thesis chapter)

Land managers have been using fuel treatments to reduce fuel loads and alter fuel continuity in ponderosa pine (*Pinus ponderosa*) forests often for ecosystem restoration and to mitigate high severity wildfire effects. The 2007 Egley Fire Complex intersected pre-fire fuel treatments in the dry ponderosa pine dominated Malheur National Forest in eastern Oregon. Post-fire vegetation response was monitored annually using annual Normalized Burn Ratio (NBR) images fitted by Landsat time series (LandTrendr) and assessed at 35 paired (treated versus untreated) field sites. This study sought to 1) analyze to what extent remotely sensed burn severity, as indicated by differenced pre- minus post-fire NBR (dNBR), related to ground measurements one and nine years post-fire, 2) compare post-fire overstory, understory, and fuel loading components between treated and untreated areas and, 3) evaluate changes in overstory and understory components over time.

A MRBP test confirms significantly lower dNBR in treated sites compared to untreated sites ($P < 0.001$, A = 0.27) within the Egley Fire Complex, demonstrating that fuel reduction treatments mitigated severe wildfire effects. LandTrendr analysis showed the Normalized Burn Ratio (NBR) decreased sharply following the fire, more so in untreated-high severity sites, then increased gradually as vegetation recovered, more so in treated sites. Differenced Normalized Burn Ratio (dNBR) moderately correlated with 2008 ground burn severity measurements (R^2 =

0.636, *P* < 0.001). Live tree density was more effected by severity than treatment in either year (both *P* < 0.001), whereas only dead tree density was significant in 2008. Understory grass cover (%) in 2008 was significantly higher in treated-low severity sites than treated- and untreated-high severity sites (both *P* ≤ 0.044) where as in 2016, grass cover was significantly higher in untreated-high severity sites than treated- and untreated-low severity sites (both *P* ≤ 0.016). No differences in total fuel loadings were detected in 2008, but total fuel loadings in 2016 were significantly higher in untreated-high severity sites than all other treatment-severity groups (*P* = 0.013) (Fig. 11).

Results confirm that pre-fire fuel treatments were effective at reducing burn severity. Burn severity effects of the Egley Fire Complex were successfully captured by LandTrendr analysis. Both one-year post-fire NBR and dNBR were moderately correlated with 2008 ground burn severity measurements, especially char and tree canopy cover. Mechanical thinning was effective at reducing pre-fire tree and sapling density, likely causing the majority of treated sites to have burned at low severity. Understory grass, forb, and invasive cover was higher in high severity sites than low severity sites, most likely promoted by the increase in light exposure post-fire. Fuel loadings were highest in 2016 untreated-high severity sites, indicating that the Egley Fire Complex and mechanical treatments were successful at reducing fuel loadings. These results support the implementation of fuel treatments to reduce fire effects in ponderosa pine forests, and suggest that low severity wildfire can accomplish fuel reduction treatment objectives while not overly increasing overstory tree mortality.

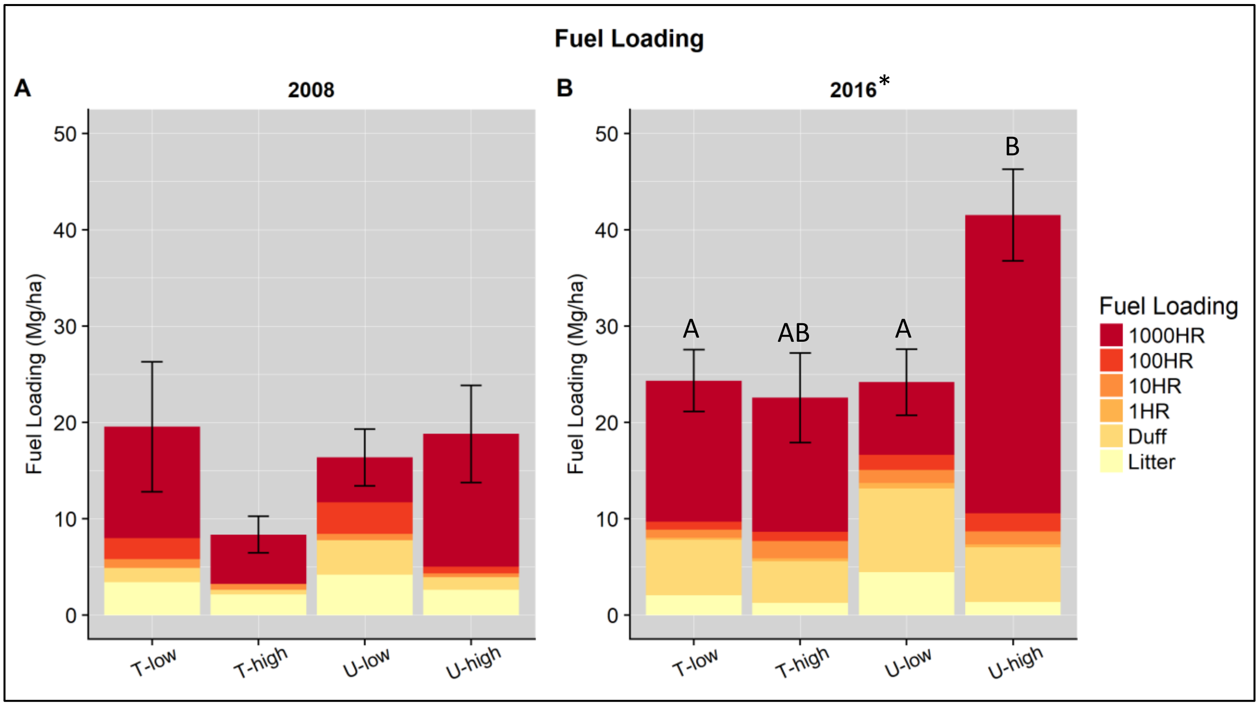

Figure 11. Stacked column graph showing fuel loadings (Mg/ha) for A) 2008 and B) 2016 contrasting treated vs. untreated and low vs. high severity; T=treated, U=untreated. Standard error bars are for total surface fuels (all fuel components added together). Significance: *, P < 0.05.

4.6 Functional group responses to burn severity in three ponderosa pine ecosystems a decade after fire

Authors: Newingham, B.A., A.T. Hudak, A.G. Smith, and B.C. Bright.

Plant responses to burn severity likely interact with climate, where recovery after fire may be slowest in drier and hotter areas. We assessed vegetation recovery 9-15 years post-fire in three ponderosa pine ecosystems (Oregon, Colorado, and South Dakota) distributed across burn severity and climatic gradients. Using non-metric multidimensional scaling, we assessed the importance of climate on understory plant communities. Mean annual precipitation after fire was the most significant climate variable. Using multiple regressions, we examined the effects of burn severity, elevation, aspect, and precipitation after fire on total, shrub, grass, and forb cover, as well as total Shannon's diversity. At the driest fire in Oregon, burn severity had significant positive effects on total, native, and introduced cover, as well as introduced grass, and native forb cover. Elevation positively affected and precipitation negatively affected diversity (Table 3). In Colorado, burn severity significantly affected total, native and introduced cover, while also affected native grass, introduced forb, and native forb cover. Elevation in Colorado significantly affected native grass cover and diversity, and precipitation significantly affected introduced cover and diversity (Table 3). Only burn severity affected diversity at the wettest fire in South Dakota (Table 3). We concluded that ponderosa pine forest recovery after fire depends on local climate and burn severity. Additionally, time since fire may also explain remaining burn severity effects on ponderosa pine understory communities.

Table 3. Summary of variable effects significantly influenced by burn severity (dNBR), annual precipitation after the fire (Precip.) and elevation, 9-15 years post fire in three different ponderosa pine ecosystems. + = positive effect; - = negative effect.

	Measured Variable	**Egley,OR**	**Hayman, CO**	**Jasper, SD**
Cover	Total	dNBR +	dNBR +	.
	Native	dNBR +	dNBR +	.
	Introduced	dNBR +	dNBR + Precip -	.
Diversity	Shannon's	Precip - Elevation +	dNBR + Precip - Elevation -	dNBR +
Functional Group Cover	Native Grass	.	. dNBR + Elevation -	.
	Introduced Grass	dNBR +	Precip -	.
	Native Forb	dNBR +	dNBR +	.
	Introduced Forb	.	dNBR +	.

4.7 The role of shrubs in chaparral plant community recovery along burn severity gradients a decade after fire

Authors: Smith, A.G., Newingham, B.A., A.T. Hudak, and B.C. Bright

In chaparral ecosystems, short-term post-fire studies have shown native shrub cover is negatively associated with introduced forb and graminoid cover, and influenced by burn severity, elevation, aspect, and climate. Previous long-term remote sensing studies found differences in shrub recovery depend on climate. We sought to understand the role of native shrubs in post-fire recovery across biotic and abiotic variables linking field and remote sensing data. Using Landsat imagery derived Normalized Burn Ratio (NBR) as an indicator of green vegetation, we determined that sites burned at moderate and high burn severity have not returned to pre-fire levels of greenness, whereas sites burned at low burn severity have. For ground truth, we estimated percent cover of functional groups at nested sampling sites distributed across burn severity, elevation, aspect, and time using non-metric multidimensional scaling and mixed effects models. By year twelve, burn severity was not a significant predictor of shrub cover but remained predictive for forbs and graminoids. This may imply shrubs are more resilient to burn severity. We found high shrub cover to be a significant predictor of low introduced richness and high native cover (Fig. 12), suggesting native shrubs may competitively exclude introduced species and have a facilitative effect on native species.

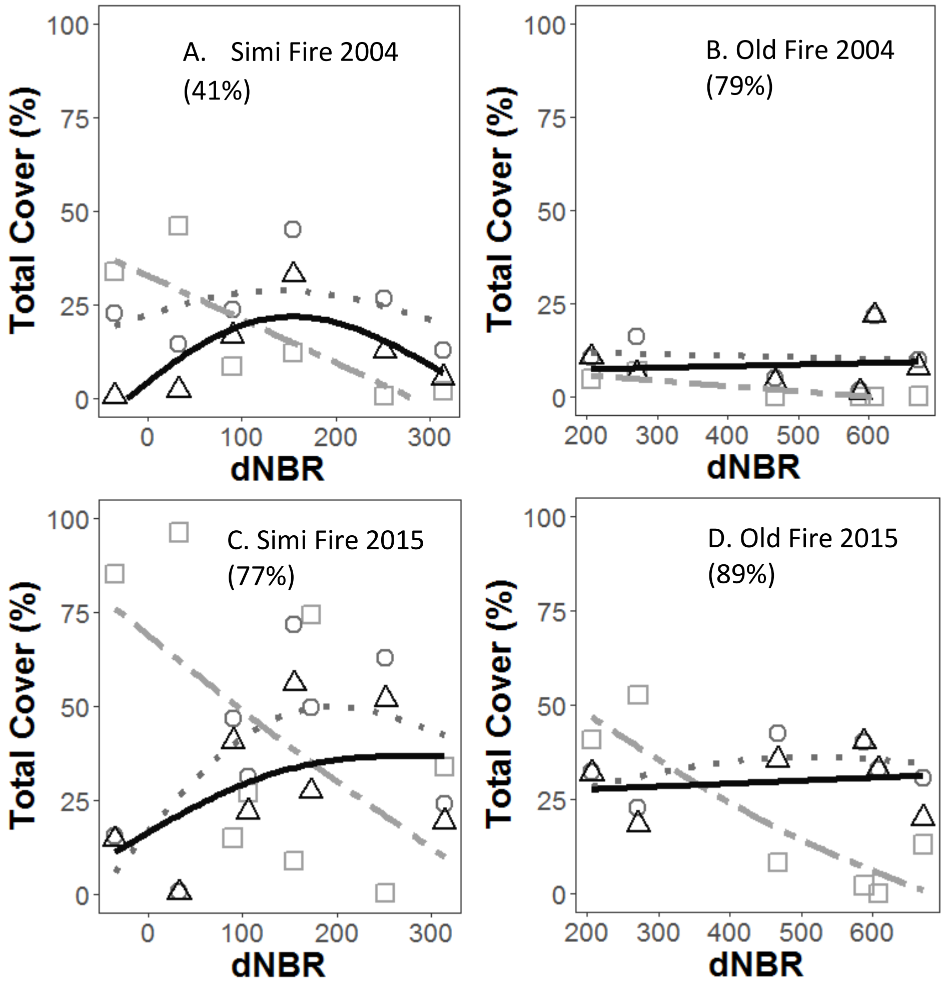

Figure 12. Effect of burn severity on shrub, introduced, and native cover at the Old and Simi Fires, southern CA one year and twelve years post fire. Solid line and triangles indicate shrub cover. Dotted line and circles indicate native cover. Dash-dot lines and squares indicate introduced cover. Numbers in parenthesis are the percent of native cover made up by shrubs.

4.8 Long-term effects of burn severity on Alaska boreal forest understory following 2004 wildfires

Authors: Darcy H. Hammond, Eva K. Strand, Andrew T. Hudak, Beth A. Newingham, John Byrne (PhD dissertation chapter)

Fire-prone boreal forests of Alaska are at risk of increased wildfire frequency, size, and severity as the climate warms, resulting in possible cascading changes to overstory tree dominance and understory plant composition. In order to provide a more complete picture of lingering burn severity effects, we sampled residual mature trees, tree regeneration, woody fuels, and understory vegetation along a burn severity gradient 12 years after the 2004 Taylor Highway Complex in Interior Alaska. We also compared species composition and cover in re-measured sites one and 12 years post-fire.

Burn severity index (dNBR) was linearly correlated with both live and dead tree stem density but not with moss or duff depth. Spruce seedling and hardwood sapling density were not significantly different among severity groups, but median spruce seedling density in high severity was half that of other areas. Low and moderate severity sites had significantly higher 1hr and 100hr fuel loads. Understory plant composition in unburned sites was different than moderate and high sites; an indicator species analysis identified multiple moss, forb, and lichen species that are significant indicators of past burn severity. Ordination analysis showed that overstory (live stems per ha, dead basal area), understory (moss and duff depth, fuel loading), and site (elevation, aspect, burn severity) drives understory community composition (Fig. 13).

Remotely-sensed burn severity strongly predicted live and dead tree density but did not predict moss or duff depth well. Despite high variation, spruce seedling density in high severity sites was on average approximately half that of other sites. Low severity sites had generally the highest fuel loading, which may make them less suitable as natural firebreaks for future fires, although the reduction in live stem density would still result in a decrease in future fire behavior. Understory plant communities differed among unburned and moderate and high severity with community composition correlated with multiple overstory, understory, and site factors. Overall, we found no indication of uncharacteristic shifts in understory plant community and generally strong regeneration of spruce seedlings though in lower numbers at high severity sites.

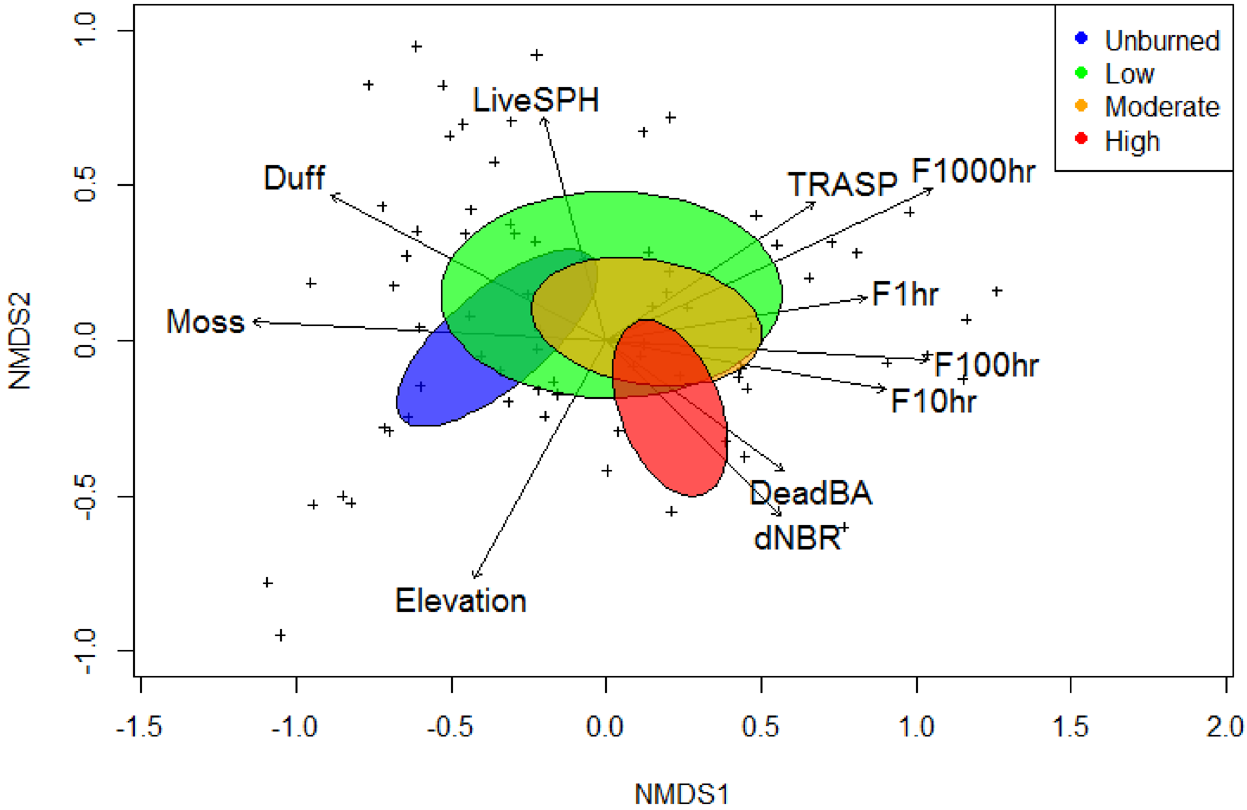

Figure 13. Non-metric multidimentional scaling (cumulative R^2~0.81) results showing individual species plotted in the background with a joint bi-plot of environmental covariables where arrows indicate direction of correlation and the length of the arrow indicates strength of the correlation. Ovals represent standard error around the location of the sites as plotted in ordination space. The final number of dimensions was three, with stress = 0.013.

4.9 Monitoring long-term post-fire vegetation recovery using LandTrendr

Authors: Benjamin C. Bright, Andrew T. Hudak, Robert E. Kennedy

Few studies have examined post-fire vegetation recovery in temperate forest ecosystems with Landsat time series analysis. We analyzed time series of Normalized Burn Ratio (NBR) derived from LandTrendr spectral-temporal segmentation fitting to examine post-fire NBR recovery for several wildfires that occurred in three different coniferous forest types in western North America during the years 2000-2007. We summarized NBR recovery trends, and investigated the influence of burn severity, post-fire climate, and topography on post-fire vegetation recovery via Random Forests (RF) analysis.

As a proxy for vegetation cover, NBR recovery across fire events averaged 33-70% nine years post fire and 42-77% 13 years post fire, and varied by time since fire, severity, and fire event. Recovery rates were generally greatest for several years following fire (Fig. 14). Recovery in terms of percent NBR was often greater for higher severity patches. Recovery rates varied between forest types, with conifer/oak/chaparral showing the greatest recovery rates, mixed conifer showing intermediate rates, and ponderosa pine showing slowest rates. Between 1-28% of patches had recovered to pre-fire NBR levels 9-16 years after fire, with greater percentages of low severity patches showing full recovery. Precipitation decreased and temperatures generally remained the same or increased post fire. Pre-fire NBR and burn severity were important predictors of NBR recovery for most fires, and explained 0-23% of the variation in post-fire NBR recovery. Post-fire climate anomalies were also important predictors of NBR recovery and explained an additional 28-41% of the variation in post-fire NBR recovery.

Landsat time series analysis was a useful means of describing and analyzing post-fire vegetation recovery across mixed-severity wildfire extents. We demonstrated that a relationship exists between post-fire vegetation recovery and climate in temperate ecosystems of western North America. Our methods could be applied to other burned landscapes where spatially-explicit measurements of post-fire vegetation recovery are needed.

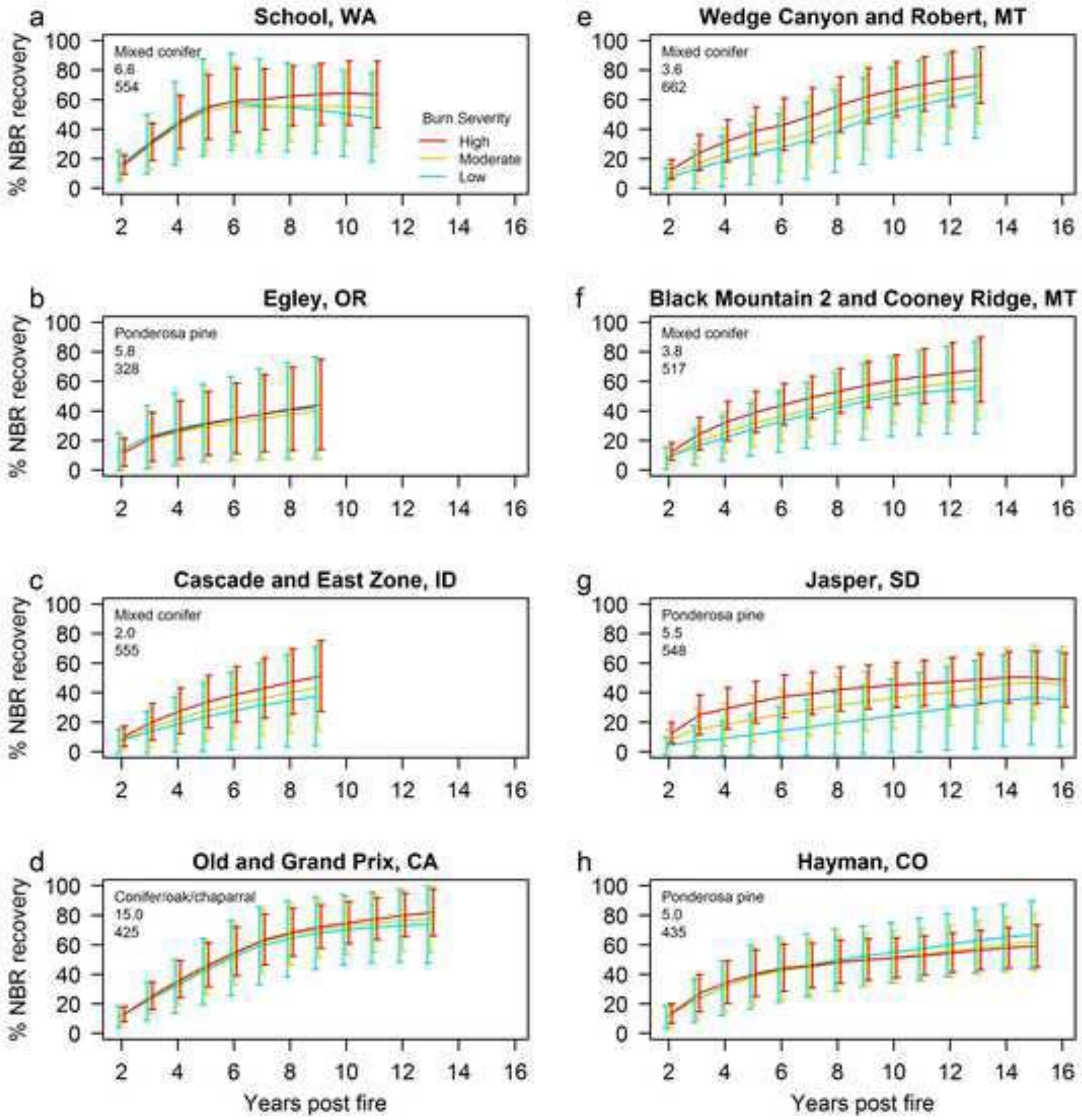

Figure 14. Time series of percent recovery of mean percent Normalized Burn Ratio (NBR) by burn severity for fires considered in the western U.S. Bars show ± 1 standard deviation. NBR recovery rates varied by fire, severity, and time since fire.

4.10 Reburns and fire-on-fire interactions in U.S. northern Rocky Mountain forests

Authors: Justin B. Laurer, Penelope Morgan, Camille Stevens-Rumann, Eva K. Strand, Andrew T. Hudak

Fire-on-fire interactions, where a fire encounters the perimeter and burned area of a previous fire, will likely increase as large fires become more frequent across the western US. Where fires are limited in size by previous fires, this could improve land and fire management and lower fire suppression costs. We analyzed fire perimeters recorded for 9.7 million forested ha of the U.S. Northern Rockies from 1900 to 2014 to examine fire-on-fire interactions by landscape characteristics and different fire and land management strategies. We found that less than 10% of the total area burned more than once. Fires overlapped more during regional fire years, in wilderness, in dry forests, especially later in our study period (1974-2014), with increasing years since previous fire events, and at higher elevation. Distance between fires increased as aspect moved from north-northeast to south-southwest. Fire-on-fire interactions did not vary significantly with slope.

We analyzed a larger area, including both wilderness and non-wilderness, and a much longer time frame compared to previous studies that were largely limited to wilderness areas and ~30 years of satellite imagery, and we came to similar conclusions. Our study demonstrated that fire extent is limited by previous fires on the landscape even over longer-time periods, which is an important management consideration. We analyzed reburn and the degree to which prior fires influence extent of subsequent fires using data from 1900-2014 from more than 9 million hectares of forest, both within and outside of wilderness and spanning multiple fire management errors, and environmental conditions. No one else has addressed this questions over such an expanse of time and space. Our findings are of theoretical interest to those who evaluate self-regulation of landscape change, and they will inform fire managers who often use footprints of prior fires to help them limit size and severity of fires.

4.11 Workshop: Long-Term Vegetation Recovery and Reburn Potential

A 2-day workshop on Long-Term Vegetation Recovery and Reburn Potential was held June 11-13, 2018 at the McCall Outdoor Science School (MOSS) in McCall, ID. PI Hudak (USDA FS-RMRS) and Co-PIs Strand (University of Idaho) and Newingham (USDA-ARS) co-organized the workshop in partnership with Susan Prichard (University of Washington) and Bob Gray (private consultant in British Columbia), the PI and Co-PI, respectively, of another JFSP project entitled “Evaluation of past-fire burn mosaics on subsequent wildfire behavior, severity and fire management strategies,” which was also funded in FY14 in response to the same task statement. Our project presented results on long-term vegetation recovery while Prichard’s project presented results on modeling reburn potential, with both projects focusing on the nearby East Zone and Cascade Complex mega-fires of 2007. (The 2007 East Zone and Cascade Complex mega-fires together burned >0.5M acres of mostly Payette and Boise National Forest lands east of McCall.) Linking our research results satisfied a mutual commitment to collaborate on a workshop with managers, a deliverable that we had both promised in our proposals.

The workshop was attended by 22 managers or researchers interested in monitoring long-term (~10 years) vegetation composition and cover conditions following wildfires, and the longer-term implications, including reburn potential, of older wildfires for fuels and fire management. Ten oral presentations were given by researchers or graduate students. University of Idaho graduate students Darcy Hammond and Jessie Dodge coordinated workshop logistics, in partnership with the JFSP-funded Fire Science Exchange Network, represented by Science Applications Specialist Vita Wright and Megan Keville, who videotaped the presentations to make them available on the Northern Rockies Fire Science Network website, along with the Powerpoint files as PDFs, for the public and particularly managers who were unable to attend. The field trip on 12 June (Fig. 15) focused on reburn areas, where the 2007 East Zone Complex reburned portions of the 2000 Burgdorf Fire and 1994 Chicken Fire. Presentations were recorded and will be posted on the Northern Rockies Fire Science Network (https://www.nrfirescience.org/).

The workshop also provided an opportunity for workshop attendees to evaluate future priorities for post-fire vegetation research and management. A Q-Sort survey was conducted by University of Idaho social science graduate students Catrin Edgeley and Amanda Stasiewicz and revealed some common areas of prioritization among fire scientists and managers (e.g., fuel treatment effectiveness, influence of burn mosaics on fire management) and some differences, which led to an engaging and productive final discussion between scientists and managers.

Figure 15. Long-term Vegetation Recovery and Reburn Potential Workshop attendees who participated on the field trip to the East Zone Complex, pausing for a group photo at the post office in Warren, ID.

V. Conclusions (Key Findings) and Implications for Management/Policy and Future Research

5.1 Conclusions

In general, we were struck by how well vegetation had recovered regardless of burn severity, according to our vegetation metrics, on almost all the fires we revisited. Initial concerns soon after these large wildfire events--that high severity burns would slow vegetation regrowth, promote colonization by invasives, diminish diversity for many years post-fire, or exhibit poor tree seedling regeneration—didn't really play out. The plants in these ecosystems, for the most part, seem to be responding well within their capacity to adapt to high severity fire. Across the seven large wildfires we sampled in the Interior Northwest, we found compelling evidence for plant species diversity a decade post-fire being highest at moderate burn severity sites. We did not find strong evidence for persistent high severity effects at any of our 15 fires, with the notable exception of the 2002 Hayman Fire, which by most of our measures (field and remote) was an extreme event. It may exemplify a shift from a ponderosa pine forest type to a shrub-dominated community. Climate is a better predictor of our recovery metrics in ponderosa pine forests than in the other ecosystems we've tested.

This was a big project especially in terms of the fieldwork effort. We sampled 15 older wildfires that burned between 2000 and 2007, across 5 vegetation types broadly representative of much of the western USA and interior Alaska. We collected plot data at 5 plots per site at 248 sites, 158 of which were re-measured existing sites, thus affording the opportunity to quantify vegetation change since one year post-fire. Our balanced sampling design allows us to make inferences across these entire landscapes sampled. By our design, five 30m resolution Landsat pixels per site were characterized with five geolocated plots on the ground, which added strength to the relationships upon aggregation. This is an important consideration for efficiently relating field plots to moderate resolution (e.g., 30 m) imagery. The strong correlation between vegetation cover and the satellite NBR index makes it possible to infer vegetation cover across these whole landscapes. This "scalability" of percent vegetation cover estimated from field or satellite observations make it our recommended metric for long-term vegetation monitoring. The continuity of the Landsat image archive since 1972 make it the recommended image data source for consistent, remote monitoring of long-term vegetation recovery across the landscape.

It was valuable to hold our workshop with managers near the end of the project period, which was timely after having analyzed our datasets, to better incorporate their feedback as we write the publications. One lesson solidified at the workshop was that burn severity is fuel driven at fine scales. At larger scales, burn severity is not increasing as a proportion of area burned. However, burn area certainly is increasing and will continue to increase as the climate warms, dries, and fire seasons extend. Older burns can act as a firebreak to aid in fire suppression, but probably not reliably after about 15 years, when enough new fuel has accumulated to create potential for reburn. Reburned areas are much less likely to recover. Indeed, a discovery made at the workshop was that it's useful to unpack the word "recover"; to re-cover—literally, to "cover" anew with vegetation. It's useful to take the conservative view of the term to help prevent its future misuse, however unintended.

We believe this project was a good investment by the JFSP and demonstrates a sound strategy for measuring vegetation recovery on the ground and remotely. Our quantitative results largely confirm what many managers on the land have long thought intuitively. It is therefore helping them. Future research should consider other ecosystems, particularly rangeland ecosystems, and the lower latitude or altitudinal margins of forest ecosystems at the frontlines of climate change.

VI. Literature Cited

Eidenshink, J., B. Schwind, K. Brewer, Z. Zhu, B. Quayle, and S. Howard. (2007) A project for monitoring trends in burn severity. *Fire Ecology* 3(1): 3-21.

Gorelick N, Hancher M, Dixon M, Ilyushchenko S, Thau D, Moore R (2017) Google Earth Engine: Planetary-scale geospatial analysis for everyone. *Remote Sensing of Environment* 202:18-27. doi: 10.1016/j.rse.2017.06.031.

Hicke, J.A., G.P. Asner, E.S. Kasishke, N.H.F. French, J.T. Randerson, J.G. Collatz, B.J. Stocks, C.J. Tucker, S.O. Los, and C.B. Field. (2003) Postfire response of North American boreal forest and primary productivity analyzed with satellite observations. *Global Change Biology* 9: 1145-1157.

Hudak, A.T., P.H. Freeborn, S.A. Lewis, S.M. Hood, H.Y. Smith, C.C. Hardy, R.J. Kremens, B.W. Butler, C. Teske, R.G. Tissell, L.P. Queen, B.L. Nordgren, B.C. Bright, P. Morgan, P.J. Riggan, L. Macholz, L.B. Lentile, J.P. Riddering and E.E. Mathews. (2018) The Cooney Ridge Fire Experiment: An early operation to relate pre-, active, and post-fire field and remotely sensed measurements. *Fire* 1: 10. DOI: 10.3390/fire1010010.

Hudak, Andrew T., Ian Rickert, Penelope Morgan, Eva Strand, Sarah A. Lewis, Peter R. Robichaud, Chad Hoffman and Zachary A. Holden. (2011) Review of fuel treatment effectiveness in forests and rangelands and a case study from the 2007 megafires in central, Idaho, USA. Gen. Tech. Rep. RMRS-GTR-252 Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 60 p.

Hudak, A.T., P. Morgan, M.J. Bobbitt, A.M.S. Smith, S.A. Lewis, L.B. Lentile, P.R. Robichaud, J.T. Clark, and R.A. McKinley. (2007) The relationship of multispectral satellite imagery to immediate fire effects. *Fire Ecology* 3(1): 64-90.

Kashian, D.M., W.H. Romme, D.B. Tinker, M.G. Turner, and M.G. Ryan. (2006) Carbon storage on landscapes with stand-replacing fires. *BioScience* 56(7): 598-606.

Keane, R.E., and L.J. Dickinson. (2007) The photoload sampling technique: estimating surface fuel loadings from downward-looking photographs of synthetic fuelbeds. Gen. Tech. Rep. RMRS-GTR-190 Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 44 p.

Keeley, J.E. 2009 Fire intensity, fire severity and burn severity: a brief review and suggested usage. *International Journal of Wildland Fire*18:116–126.

Kennedy RE, Yang Z, Cohen WB, Pfaff E, Braaten J, Nelson P (2012) Spatial and temporal patterns of forest disturbance and regrowth within the area of the Northwest Forest Plan. *Remote Sensing of Environment* 122:117-133. doi: 10.1016/j.rse.2011.09.024.

Kennedy RE, Yang Z, Gorelick N, Braaten J, Cavalcante L, Cohen WB, Healey S (2018) Implementation of the LandTrendr Algorithm on Google Earth Engine. *Remote Sensing* 10:691. doi: 10.3390/rs10050691.

Key, C.H., and Benson, N.C. 2006. Landscape assessment: sampling and analysis methods. *In* FIREMON: Fire Effects Monitoring and Inventory System. General Technical Report RMRS-GTR-164-CD. *Edited by* Duncan C. Lutes, R.E. Keane, John F. Caratti, Carl H. Key, Nathan C. Benson, S. Sutherland, and L.J. Gangi. USDA Forest Service, Rocky Mountain Research Station, Fort Collins, CO USA.

Lentile, L.B., Z.A. Holden, A.M.S. Smith, M.J. Falkowski, A.T. Hudak, P. Morgan, S.A. Lewis, P.E. Gessler, and N.C. Benson. (2006) Remote sensing techniques to assess active fire characteristics and post-fire effects. *International Journal of Wildland Fire* 15(3): 319-345.

Lentile, L.B., P. Morgan, A.T. Hudak, M.J. Bobbitt, S.A. Lewis, A.M.S. Smith, and P.R. Robichaud. (2007) Burn severity and vegetation response following eight large wildfires across the western US. *Fire Ecol.* 3(1): 91-108.

Lentile L.B., A.M.S. Smith, A.T. Hudak, P. Morgan, M.J. Bobbitt, S.A. Lewis, and P.R. Robichaud. (2009) Remote sensing for prediction of 1-year post-fire ecosystem condition. *Int. Journal of Wildland Fire* 18(5): 594-608.

Lewis, S.A., A.T. Hudak, P.R. Robichaud, P. Morgan, K.L. Satterberg, E.K. Strand, A.M.S. Smith, J.A. Zamudio and L.B. Lentile. 2017. Indicators of burn severity and ecosystem response in mixed conifer forests of western Montana. *International Journal of Wildland Fire* 26: 755-771. DOI: 10.1071/WF17019.

Littell, J.S., D. McKenzie, D.L. Peterson, and A.L. Westerling. (2009) Climate and wildfire area burned in western U.S. ecoprovinces, 1916-2003. *Ecological Applications* 19: 1003-21.

Masek JG, Vermote EF, Saleous NE, Wolfe R, Hall FG, Huemmrich KF, Gao F, Kutler J, Lim T-K (2006) A Landsat surface reflectance dataset for North America, 1990-2000. *IEEE Geoscience and Remote Sensing Letters* 3:68-72. doi: 10.1109/LGRS.2005.857030.

Miller, J., H. Safford, M. Crimmins, and A. Thode. 2009. Quantitative evidence for increasing forest fire severity in the Sierra Nevada and Southern Cascade Mountains, California and Nevada, USA. *Ecosystems* 12(1): 16-32.

Mitchell, R.G., and H.K. Preisler. (1998) Fall rate of lodgepole pine killed by mountain pine beetle in central Oregon. *Western Journal of Applied Forestry* 13: 23-26.

Roy DP, Kovalskyy V, Zhang HK, Vermote EF, Yan L, Kumar SS, Egorov A (2016) Characterization of Landsat-7 to Landsat-8 reflective wavelength and normalized difference vegetation index continuity. *Remote Sensing of Environment* 185:57-70.

Smith, A.M.S., L.B. Lentile, A.T. Hudak, and P. Morgan. (2007) Evaluation of linear spectral unmixing and dNBR for predicting post-fire recovery in a North American ponderosa pine forest. *International Journal of Remote Sensing* 28(22): 5159-5166.

Teske, C.C., C.A. Seielstad, and L.P. Queen. (2012) Characterizing fire-on-fire interactions in three large wilderness areas. *Fire Ecology* 8(2): 82-106.

Turner, M.G. (2010) Disturbance and landscape dynamics in a changing world. *Ecology* 91(10): 2833-2849.

Vermote E, Justice C, Claverie M, Franch B (2016) Preliminary analysis of the performance of the Landsat 8/OLI land surface reflectance product. *Remote Sensing of Environment* 185:46-56. doi: 10.1016/j.rse.2016.04.008.

Zhu Z, Wang S, Woodcock CE (2015) Improvement and expansion of the Fmask algorithm: Cloud, cloud shadow, and snow detection for Landsats 4–7, 8, and Sentinel 2 images. *Remote Sensing of Environment* 159:269-277. doi: 10.1016/j.rse.2014.12.014.

Appendix A: Contact Information for Key Project Personnel

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Appendix B: ***List of Completed/Planned Scientific/Technical Publications/Science Delivery Products***

Articles in peer-reviewed journals

Klauberg, C., A.T. Hudak, C.A. Silva, S.A. Lewis, P.R. Robichaud, T. Jain and P. Morgan. Predicting fire effects on conifers at tree level from airborne laser scanning and multispectral data. *Forest Ecology and Management*, in prep.

Newingham, B.A., A.T. Hudak, A.G. Smith and B.C. Bright. Functional group responses to burn severity in three ponderosa pine ecosystems a decade after fire. *Fire Ecology*, in prep.

Smith, A.G., B.A. Newingham, A.T. Hudak and B.C. Bright. The role of shrubs in chaparral plant community recovery along burn severity gradients a decade after fire. *Fire Ecology*, in prep.

Dodge, J.M., E.K. Strand, A.T. Hudak, B.C. Bright and D.H. Hammond. Effectiveness of fuel treatments tested by wildfire in ponderosa pine forest. *Fire Ecology*, in prep.

Hammond, D.H., E.K. Strand, A.T. hudak, B.A. Newingham and J. Byrne. Long-term effects of burn severity on Alaska boreal forest understory following 2004 wildfires. *Fire Ecology*, in prep.

Strand, E.K., K.L. Satterberg, A.T. Hudak, J.C. Byrne and A.M.S. Smith. Understory plant community response along a burn severity gradient ten years post-fire in mixed conifer forest of the intermountain western USA. *Fire Ecology*, in prep.

Bright, B.C., A.T. Hudak and R.E. Kennedy. Monitoring long-term post-fire vegetation recovery using LandTrendr. *Fire Ecology*, in review.

Bontrager, J.D., P. Morgan, A.T. Hudak and P.R. Robichaud. Long-term vegetation response following post-fire straw mulching. *Fire Ecology*, in review.

Laurer, J.B., P. Morgan, C. Stevens-Rumann, E.K. Strand and A.T. Hudak. Reburns and fire-on-fire interactions in U.S. northern Rocky Mountain forests. *Fire Ecology*, in revision.

Stevens-Rumann, C., A.T. Hudak, P. Morgan and A. Arnold. Fuel dynamics following wildfire in the US Northern Rockies forests. *Fire Ecology*, in revision.

Hudak, A.T., P.H. Freeborn, S.A. Lewis, S.M. Hood, H.Y. Smith, C.C. Hardy, R.J. Kremens, B.W. Butler, C. Teske, R.G. Tissell, L.P. Queen, B.L. Nordgren, B.C. Bright, P. Morgan, P.J. Riggan, L. Macholz, L.B. Lentile, J.P. Riddering and E.E. Mathews. (2018) The Cooney Ridge Fire Experiment: An early operation to relate pre-, active, and post-fire field and remotely sensed measurements. *Fire* 1: 10. DOI: 10.3390/fire1010010.

Lewis, S.A., A.T. Hudak, P.R. Robichaud, P. Morgan, K.L. Satterberg, E.K. Strand, A.M.S. Smith, J.A. Zamudio and L.B. Lentile. (2017) Indicators of burn severity and ecosystem response in mixed conifer forests of western Montana. *International Journal of Wildland Fire* 26: 755-771. DOI: 10.1071/WF17019.

Graduate theses (masters or doctoral)

Darcy Hammond (PhD, Fire Ecology focus, Spring 2019)
Jessie Dodge (Master of Science, Fire Ecology focus, Spring 2019)
Eli Berman (Master of Natural Resources, Fire option, Spring 2018)
Jonathan Bontrager (Master of Science, Fire Ecology focus, Spring 2017)
Justin Laurer (Master of Science, Fire Ecology focus, Spring 2017)
Mattie Schmidt (Senior Thesis Project, B.S. Rangeland Ecology and Management, Spring 2017)
Kevin Satterberg (Master of Science, Fire Ecology focus, Fall 2015)

Conference or symposium abstracts

Newingham, B.A., A.T. Hudak, B.C. Bright, A.G. Smith and A. Henareh Khalyani. Burn severity effects on multiple ecosystem recovery trajectories. AFE/IAWF Fire Continuum Conference, Missoula, Montana, 21-24 May 2018. (oral presenation, published abstract).

Smith, A.G., B.A. Newingham, A.T. Hudak and B.C. Bright. Got shrubs? Burn severity effects on chaparral plant community recovery a decade after fire. Society for Range Management Annual Meeting, Sparks, Nevada, 28 Jan - 2 Feb 2018. (oral presentation, published abstract).

Newingham, B.A., A.T. Hudak, B.C. Bright, A.G. Smith and A.H. Khalyani. Post-fire ecosystem recovery trajectories along burn severity gradients. American Geophysical Union Annual Meeting, New Orleans, Louisiana, 22-15 Dec 2017. (oral presentation, published abstract).

Lewis, S.A., A.T. Hudak, P.R. Robichaud#, A decade of ecosystem response: post-fire indicators of burn severity and recovery in mixed conifer forests of western Montana. Association for Fire Ecology Congress, Orlando, Florida, 28 Nov – 2 Dec 2017. (oral presentation, published abstract).

Bright, B.C., A.T. Hudak# and R.E. Kennedy. Examining post-fire vegetation recovery with Landsat time series data in four western North American ecosystems.

Association for Fire Ecology Congress, Orlando, Florida, 28 Nov – 2 Dec 2017. (oral presentation, published abstract).

Smith, A.G., B.A. Newingham, A.T. Hudak and B.C. Bright. The role of shrubs in chaparral plant community recovery along burn severity gradients a decade after fire. Association for Fire Ecology Congress, Orlando, Florida, 28 Nov – 2 Dec 2017. (oral presentation, published abstract).

Newingham, B.A., A.T. Hudak, A.G. Smith, B.C. Bright and A.H. Khalyani. Functional group responses to burn severity in three ponderosa pine ecosystems a decade after fire. Association for Fire Ecology Congress, Orlando, Florida, 28 Nov – 2 Dec 2017. (oral presentation, published abstract).

Dodge, J., E.K. Strand, and A.T. Hudak. Do fuel treatments impact post-fire understory plant recovery and fuel loadings in ponderosa pine forests? Association for Fire Ecology Congress, Orlando, Florida, 28 Nov – 2 Dec 2017. (oral presentation, published abstract).

Hammond, D., E.K. Strand, A.T. Hudak, B.A. Newingham and J.C. Byrne. Long-term effects of burn severity on Alaska boreal forest understory following 2004 wildfires. Association for Fire Ecology Congress, Orlando, Florida, 28 Nov – 2 Dec 2017. (oral presentation, published abstract).

Strand, E.K., K.L. Satterberg, A.T. Hudak, J. Byrne and A.M.S. Smith. Does burn severity affect plant community composition in northern Rockies forests ten years post-fire? Association for Fire Ecology Congress, Orlando, Florida, 28 Nov – 2 Dec 2017. (oral presentation, published abstract).

Klauberg, C., A.T. Hudak# and C.A. Silva. Predicting immediate and extended fire effects on a mixed conifer forest at high resolution from LiDAR and multispectral imagery. Association for Fire Ecology Congress, Orlando, Florida, 28 Nov – 2 Dec 2017. (oral presentation, published abstract).

Bontrager, J., P. Morgan, P.R. Robichaud and A.T. Hudak. Long-term vegetation response following post-fire mulching. Society of American Foresters National Convention, Albuquerque, New Mexico, 15-19 Nov 2017. (poster, published abstract).

Smith, A.G., B.A. Newingham, A.T. Hudak and B.C. Bright. Chaparral plant community recovery along burn severity gradients a decade after fire. Ecological Society of America Meeting, Portland, Oregon, 6-11 Aug 2017. (oral presentation, published abstract).

Newingham, B.A., A.T. Hudak, A.G. Smith, B.C. Bright and A.H. Khalyani. Climate and burn severity effects on post-fire recovery of three ponderosa pine ecosystems. Ecological Society of America Meeting, Portland, Oregon, 6-11 Aug 2017. (oral presentation, published abstract).

Hudak, A.T., S.A. Lewis, B.C. Bright, R.E. Kennedy, K.L. Satterberg, E.K. Strand, P. Morgan, B.A. Newingham, A. Smith and L.B. Lentile. Vegetation recovery since the 2003 wildfires in western Montana. Fire Sciences Lab Seminar Series, Missoula, Montana, 28 Apr 2016. (invited oral presentation, published abstract).

Hudak, A.T., B.C. Bright, R.E. Kennedy, K.L. Satterberg, E.K. Strand, S.A. Lewis, B.A. Newingham and P. Morgan. Monitoring site recovery as a function of burn severity and time-since-burn in four western U.S. ecosystems. 6th International Fire Ecology and Management Congress, San Antonio, Texas, 17 Nov 2015. (invited oral presentation, published abstract).

Lewis, S.A., A.T. Hudak, P. Robichaud[#], P. Morgan, K.L. Satterberg, E.K. Strand, A.M.S. Smith, J.A. Zamudio and L.B. Lentile. Assessing burn severity and recovery 10 years after wildfires in western Montana. 6th International Fire Ecology and Management Congress, San Antonio, Texas, 16-20 Nov 2015. (oral presentation, published abstract).

Newingham, B.A., A.G. Smith, A.T. Hudak and E.K. Strand. What's still hot? Cross-ecosystem diversity responses a decade after fire. 6th International Fire Ecology and Management Congress, San Antonio, Texas, 16-20 Nov 2015. (oral presentation, published abstract).

Bright, B.C., A.T. Hudak[#], and R.E. Kennedy. Examining patterns of vegetation recovery following wildfire using Landsat time series analysis. 6th International Fire Ecology and Management Congress, San Antonio, Texas, 17 Nov 2015. (oral presentation, published abstract).

[#] *Presenter (if not first author)*

Posters

Hammond, D.H., E.K. Strand, A.T. Hudak, P. Morgan and B.A. Newingham. Spatial characteristics of burn severity patches and effects on post-wildfire conifer regeneration in ponderosa pine forests. AFE/IAWF Fire Continuum Conference, Missoula, Montana, 21-24 May 2018. (poster, published abstract).

Dodge, J.M., E.K. Strand, B.C. Bright and A.T. Hudak. Using Landsat and ground measurements to monitor treatment effects in ponderosa pine forests 1 and 9 years post fire. AFE/IAWF Fire Continuum Conference, Missoula, Montana, 21-24 May 2018. (poster, published abstract).

Dodge, J.M., E. Strand and A.T. Hudak. Do fuel treatments impact fire severity and post-fire understory plant recovery in ponderosa pine forests? Ecological Society of America Meeting, Portland, Oregon, 6-11 Aug 2017. (poster, published abstract).

Hammond, D.H., A.T. Hudak, B.A. Newingham and J. Byrne. Long-term effects of burn severity on boreal understory plant communities following large wildfires. Ecological Society of America Meeting, Portland, Oregon, 6-11 Aug 2017. (poster, published abstract).

Strand, E., K. Satterberg, A. Hudak, D. Hammond and A. Smith. Impact of burn severity on plant community composition, diversity, and fuels in mixed conifer forests ten years post-fire. Ecological Society of America Meeting, Portland, Oregon, 6-11 Aug 2017. (poster, published abstract).

Newingham, B.A., A.T. Hudak, B.C. Bright, and A.G. Smith. 2016. A decadal glimpse on climate and burn severity influences on ponderosa pine post-fire recovery. American Geophysical Union Fall Meeting. San Francisco, California, 12-16 Dec 2016. (poster, published abstract).

Dodge, J.M., E.K. Strand and A.T. Hudak. Do fuel treatments impact fire severity and post-fire understory plant recovery in ponderosa pine forests? Southwest Fire Ecology and Management Conference, Tucson, Arizona, 28 Nov – 2 Dec 2016. (poster, published abstract).

Schmidt, M., D.H. Hammond, A.T. Hudak, B.A. Newingham, E.K. Strand and P. Morgan. Long-term effect of burn severity on non-native plant cover. 6th International Fire Ecology and Management Congress, San Antonio, Texas, 16-20 Nov 2015. (poster, published abstract).

Lauer, J.B., P. Morgan, C. Stevens-Rumann, A.T. Hudak and E.K. Strand. Reburns and fire-on-fire perimeter interactions 1900-2013. 6th International Fire Ecology and Management Congress, San Antonio, Texas, 16-20 Nov 2015. (poster, published abstract).

Hammond, D.H., E.K. Strand, A.T. Hudak, B.A. Newingham and P. Morgan. Long-term burn severity and edge effects on conifer seedling survival following large wildfires. 6th International Fire Ecology and Management Congress, San Antonio, Texas, 16-20 Nov 2015. (poster, published abstract).

Bontrager, J.D., P. Morgan, A.T. Hudak, P.R. Robichaud and E.K. Strand. Long-term vegetation recovery of post-fire mulching treatments. 6th International Fire Ecology and Management Congress, San Antonio, Texas, 16-20 Nov 2015. (poster, published abstract).

Workshop materials and outcome reports

Workshop: Long-Term Vegetation Recovery and Reburn Potential, McCall, ID 11-13 June 2018. Video and powerpoint presentations viewable and downloadable from (https://www.nrfirescience.org/).

Field demonstration/tour summaries

Field tour of the 2007 East Zone Complex, reburn of the 2000 Burgdorf Fire reburn, wildland-urban interface (WUI) treatments around the Secesh Community, reburn of the 1994 Chicken Fire, and the historic mining town of Warren, Idaho, 12 June 2018.

Website development

FRAMES at the University of Idaho: www.frames.gov/long-term-recovery

RMRS: https://www.fs.fed.us/rmrs/projects/vegetation-recovery-forest-ecosystems-8-15-years-following-wildfire

Presentations/webinars/other outreach/science delivery materials.

Webinar: Hudak, A.T. Vegetation recovery since the 2003 wildfires in western Montana. Fire Sciences Lab Seminar Series, Missoula, Montana, 28 Apr 2016.

Graduate course: Plant community analysis (REM 504) at the University of Idaho