

FINAL REPORT

JFSP Project Number: 12-3-01-3

Project Title: Is spatial heterogeneity of burn severity changing with warming climate and increasing wildfire?



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ABSTRACT

Fire activity is increasing in most parts of the world, and trends are especially strong in the Northern Rocky Mountains. Although studies have begun to examine temporal trends in severity, surprisingly little is known about how the spatial configuration of within-fire burn severity may be changing with increasing wildfire. Broad-scale studies of trends in fire activity thus far have not characterized the ecologically significant spatial complexity within fire perimeters. In addition to temporal trends in burn severity, it is critical to understand how the spatial configuration of within-fire patterns of burn severity may be changing under a warming climate to anticipate changes in forested ecosystems and services they provide.

We examined recent (1984-2010) temporal trends in spatial patterns of burn severity in 733 large wildfires (> 200 ha) across the Northern Rockies to address two questions. (1) How has spatial heterogeneity of burn severity changed during the last 25 years, and where are these landscape patterns changing most rapidly? (2) Do changes in spatial heterogeneity of burn severity vary (a) among forest types, (b) with topographic position or levels of complexity, (c) under different land management scenarios, and (d) with climate? Field data were collected during summer 2012 on 186 fire-severity plots situated throughout the Northern Rockies in areas that burned in 2011. Fire severity for all forest fires that burned from 1984-2010 in the Northern Rockies was then mapped using the relative differenced normalized burn ratio (RdNBR) and calibrated with the postfire data ($n = 186$ plots). After determining a RdNBR threshold for stand-replacing fire using a logistic model, we converted burn severity maps to categorical maps of stand-replacing (> 90% of pre-fire live basal area killed by fire) or non-stand-replacing (> 10% of pre-fire live basal area still alive after fire) fire and tested our predictions on independent model validation plots ($n = 185$). The model performed well (overall accuracy 71%, Kappa = 0.35) and predicted that 33% of the 3,872,568 ha of forest that burned in the Northern Rockies between 1984 and 2010 was stand-replacing fire. Landscape metrics were computed for each year (using every fire in the study period) and evaluated for potential changes in burn heterogeneity over this period of warming climate and increased annual area burned, producing region-wide measures of spatial patterns in areas of stand-replacing fire.

Graduate student funding for this project has been largely to support summer field data collection, which is now complete (186 fire severity plots sampled in 2012). Most of 2013 was spent on data preparation (field data and imagery processing) and building statistical models between field measures of burn severity and RdNBR indices. Thresholds of RdNBR that relate to empirical measures of fire severity were identified. Analysis of spatial patterns of burn severity and comparisons with drivers (research question 2) is continuing with an expected completion date of December 2013. Continuing work will entail the following tasks. Region-wide maps are being produced to identify locations where the rate of change in spatial heterogeneity of burn severity is most rapid and thus the risk of landscapes shifting to alternative states may be high. Statistical relationships between downscaled (12 km x 12 km) climate variables and measures of spatial heterogeneity of burn severity for all large forest fires in the N. Rockies during the period 1984-2010 in different topographic contexts, forest types, and management settings are currently being analyzed.

Results so far have been presented at one professional conference and one agency webinar. Preparation of the first manuscript from this work is underway and submittal will be by December 2013. The second manuscript will be submitted by June 2014.

BACKGROUND AND PURPOSE

In fire-prone regions, the resiliency of forested ecosystems is greatly influenced by spatial heterogeneity of burn severity. Fire frequency and area burned are increasing in most parts of the world (Flannigan et al. 2009), but little is known about how the spatial configuration of fire severity (the effects of fire on an ecosystem) may be changing with increasing wildfire. The frequency of large forest fires has increased in the western US since the mid 1980s in association with warmer temperatures and earlier spring snowmelt (Westerling et al. 2006). This trend is strongest in Northern Rocky Mountain (N. Rockies) forests where 5 of the 11 years with the most area burned in the last century have occurred since the late 1980s (Morgan et al. 2008) and qualitative shifts in fire regimes are projected by mid 21st century (Westerling et al. 2011). Recent research has examined changes in fire activity associated with warming climate, but the spatial resolution of broad-scale studies has been largely limited to characterizing fires as points or homogeneous polygons. Regional analyses of the spatial complexity of fires have so far focused on burn perimeters (shape) only (Rollins et al. 2001, Parisien et al. 2006). While informative, this resolution overlooks the significant spatial complexity that occurs within fire perimeters. Additional research has begun to examine regional-scale trends in burn severity (Miller et al. 2008, 2011, Miller and Safford 2012), but almost no studies to date have examined potential changes in spatial heterogeneity of burn severity that may be accompanying non-spatial trends in severity.

Powerful analytic tools now exist to study spatial variability in burn severity over space and time. The multi-agency Monitoring Trends in Burn Severity project (www.mtbs.gov) provides valuable catalogued data of fire perimeters and severity indices for fires in recent years. Recent advances in burn severity indices have proven reliable over large regions and multi-decade time periods when coupled with extensive ground data (Miller et al. 2009) and landscape metrics that quantify ecologically important measures of spatial heterogeneity are well established (O'Neill et al. 1999).

Understanding how spatial patterns of burn severity may be changing under a warming climate is critical to predict broad-scale changes in forested ecosystems and the services they provide. Postfire successional trajectories, carbon storage, nutrient cycling, wildlife habitat, and hydrology are affected not only by the amount of different burn severities, but also spatial heterogeneity of burn severity (Turner et al. 2013). For example the amount and configuration of edge between burned/unburned forest patches in a fire influences distance to seed source (Turner et al. 1994, Donato et al. 2009). Assessing trends in fire severity is a top priority for informing policy in the US (Fleishman et al. 2011), and characterizing within-fire heterogeneity is important for federal fire policy (Stephens and Ruth 2005). Illustrating locations where the rate of change in disturbance severity is rapidly occurring can help forecast the potential for landscape traps (Lindenmayer et al. 2011) - areas where landscapes can be shifted to an alternative state by disturbance feedbacks. Examining links between climate and changes in spatial heterogeneity of burn severity has considerable ecological and societal relevance and is critical for informing fire management in the US. My study directly addresses the mission and goals of the Joint Fire Science Program by advancing knowledge about the relationship between climate change and fire effects.

In this study, I examine recent temporal trends in spatial patterns of burn severity in large wildfires (> 200 ha) across the N. Rockies. Using field data and remote sensing to map fire severity and analyze burn-severity patterns, I address two primary questions: *(1) How has spatial heterogeneity of burn severity changed during the last 25 years in the N. Rockies, and where are these landscape patterns changing most rapidly?* *(2) Do changes in spatial heterogeneity of burn severity vary (a) among forest types, (b) with topographic position or levels of complexity, (c) under different land management, and (d) with climate?*

STUDY DESCRIPTION AND LOCATION

The N. Rockies study region follows Westerling et al. (2011) and the JFSP boundary for the Northern Rockies Fire Science Network (<http://nrfirescience.org/>), stretching from the GYE in western Wyoming to the US/Canada border at the northern tip of Idaho. Forests are conifer-dominated and vary compositionally with elevation, moisture, and latitude (Baker 2009). Historical fire regimes range from low-frequency, high-severity (stand-replacing) regimes in higher elevation and mesic forests to more frequent, mixed-severity regimes in lower elevation forests (Baker 2009).

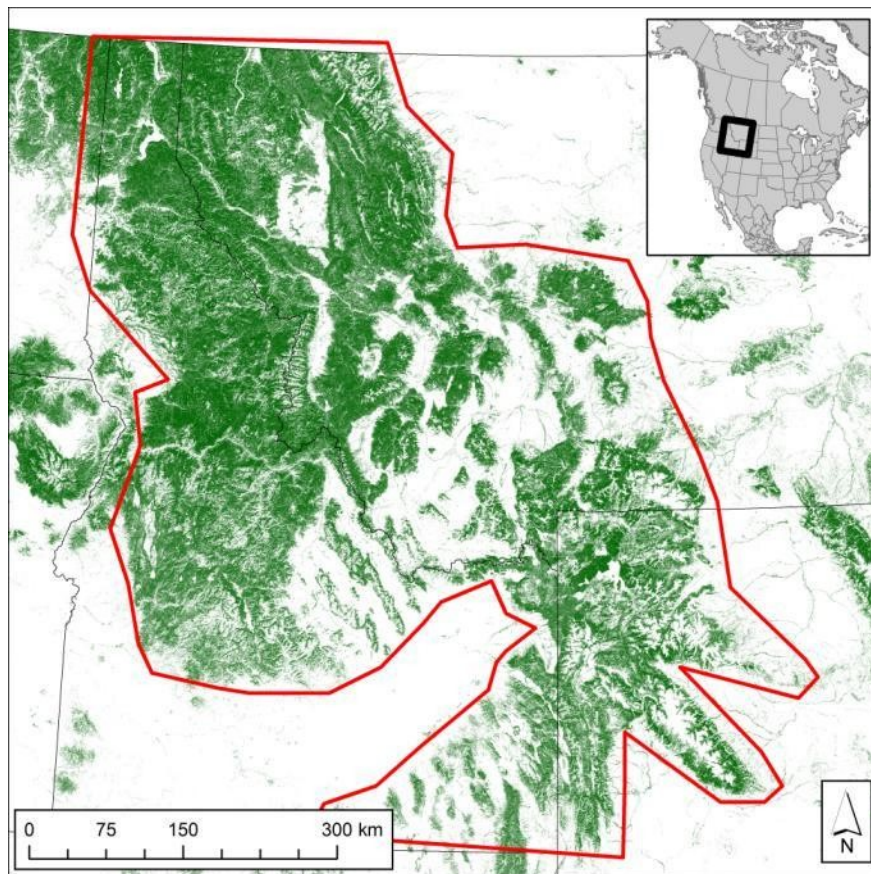


Figure 1: Northern Rockies region (study area outlined in red) and continental context (inset map). Green cells represent forested area (data source: NLCD).

Question 1: How has spatial heterogeneity of burn severity changed during the last 25 years in the N. Rockies, and where are these landscape patterns changing most rapidly?

This portion of the study combines field measurements and remotely sensed indices of fire severity to analyze spatial heterogeneity of burn severity throughout the region, and is described below in sections corresponding to each component.

Data acquisition

Fire perimeters and Landsat TM-derived burn severity layers for all fires in the study area (1984-2010) were downloaded from the Monitoring Trends in Burn Severity website (mtbs.gov). Fires occurring in non-forest areas (< 50% of area within burn perimeter was covered by forest pre-fire) were excluded. Fire severity was mapped using the relative differenced normalized burn ratio (RdNBR) provided in MTBS data for each fire. This RdNBR metric has been shown to be preferable to absolute measures of burn severity when comparing multiple fires across a wide region (Miller and Thode 2007, Miller et al. 2009). Preliminary analysis comparing RdNBR maps computed from Landsat images using top-of-atmosphere reflectance (i.e., images available on the MTBS website) vs. those calibrated to surface reflectance using the LEDAPS processing system (Masek et al. 2006) indicated no significant difference; therefore the RdNBR maps from MTBS were used for all analyses. The RdNBR raster grid for each fire was re-projected and clipped to the fire perimeter prior to analysis.

Burn severity field measurements

During summer 2012, 186 fire-severity plots were sampled in seven fires that burned in 2011 throughout the study area (Fig. 2, Table 1). Plots in each fire were located within 100-1000 m from roads and trails for accessibility, and separated by a minimum distance of 400 m to reduce spatial autocorrelation. Preliminary analysis (100 plots from a fire that burned in 2008, data not shown) showed fire severity metrics to be spatially correlated at distances up to 395 m. Each fire contained between 16 and 43 plots, depending on accessible area, and plots within a fire were equally distributed among 4 categorical fire severity classes (unburned, light surface fire, severe surface fire, and crown) (Turner et al. 1997).

We quantified fire severity in each plot using field measures of fire effects in multiple strata. Canopy-fire severity was measured on five randomly selected co-dominant canopy trees in each quadrant (20 trees per plot) by recording the maximum char height to the nearest 0.5 m and the maximum percentage of scorching around the circumference on the main bole of each selected tree. Fire-caused tree mortality was recorded by classifying every fire-damaged tree > 1.4 m in the plot that was alive at the time of fire but dead at the time of sampling as killed by fire. The percentage of post-outbreak live trees and basal area that were killed by fire was used to measure fire severity on the residual canopy after the outbreak. Surface-fire severity was measured by recording the depth of post-fire litter + duff (i.e., the soil O horizon) to the nearest mm at every 3 m along the main axis of the plot (20 pts / plot) and by recording the percent cover of charred surface (mineral soil, litter, woody debris), using the point intercept method. Points were spaced at 10-cm intervals along the main axis of the plot (480 pts / plot).

Table 1. Fires where field data were collected. Field data were collected in the 186 plots used for model development under this project; the 185 plots used for model validation were sampled under previous projects.

Fire name	Location	Fire size (ha)	Number of plots
<i>Fires for model development</i>			
Red Rock Complex	Bridger-Teton National Forest, WY	4,850	43
Salt Fire	Salmon-Challis National Forest, ID	9,916	40
Saddle Fire	Salmon-Challis National Forest, ID	12,950	40
East Fork Fire	Nez Perce National Forest, ID	4,047	16
Lutz Fire	Beaverhead-Deerlodge National Forest, MT	1,612	7
Forty-one Complex	Bitterroot National Forest, MT	6,130	21
Puzzle Creek Fire	Flathead National Forest, MT	639	16
<i>Fires for model validation</i>			
New Fork Lakes Fire	Bridger-Teton National Forest, WY	6,106	100
Gunbarrel Fire	Shoshone National Forest, WY	27,200	85

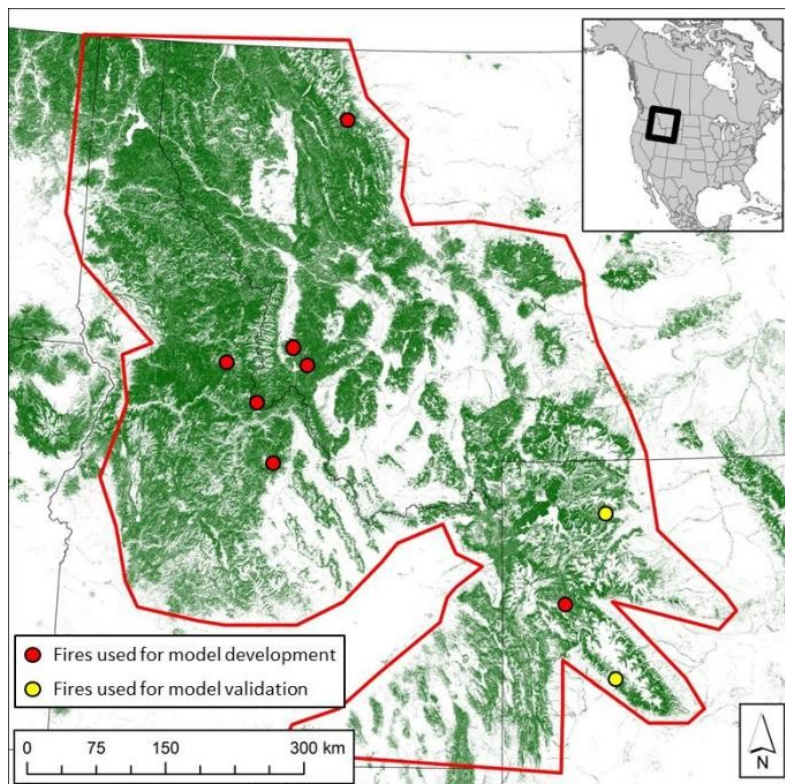


Figure 2. Location of study fires ($n = 7$) where field data were collected for model development ($n = 186$ plots in seven fires) and model validation ($n = 185$ plots in two fires). Green cells represent forested area (data source: NLCD).

Using field data to calibrate and validate burn severity maps

To calibrate RdNBR burn-severity maps to an ecologically meaningful value of stand-replacing fire, we developed statistical relationships between field measures of canopy-tree fire mortality and RdNBR values for our field data. We define stand-replacing fire to mean 90% of the pre-fire live basal area was killed by fire. Using the 186 field plots from fires that burned in 2011 (Table 1), we built linear and logistic models to test the relationship between RdNBR values and basal area killed by fire to find the best estimate of an RdNBR threshold for stand-replacing fire (> 90% of pre-fire live basal area was killed by fire). To validate the best model for predicting stand-replacing fire we used 185 independent burn severity plots from fires that burned in 2008 in the GYE. Burn severity (stand replacement or not) was predicted for each of these 185 plots based on their RdNBR value, and model performance was evaluated using predictive accuracy (user's, producer's, and overall) and the Kappa statistic. Ongoing work is mapping other levels of fire severity (e.g., unburned, low, moderate severity); however these classes of fire severity can be affected by the subjective delineation of burn perimeters. For this reason and because high-severity fire is where the greatest magnitude ecological change occurs, we focus this analysis on high-severity (stand-replacing).

Generating maps of stand-replacing fire

Using the RdNBR threshold for stand-replacing fire (90% basal area killed by fire), we converted each burn severity map to a binary fire severity map where each cell within the fire perimeter was assigned a 0 (RdNBR < stand replacement threshold) or 1 (RdNBR > stand replacement threshold). This was performed for each forest fire in the Northern Rockies (1984-2010).

Calculating landscape metrics of burn severity patterns

Landscape metrics were calculated initially on categorized burn-severity maps (stand replacing, less than stand-replacing) for each fire in the study period and combined in a mosaic raster for each year. Patches of stand-replacing fire were defined using a smoothing filter window (3x3 grid cells) and using an 8-neighbor rule for patch delineation prior to computing landscape metrics using Patch Analyst 5 for ArcGIS 10.0 (<http://www.cnfer.on.ca/SEP/patchanalyst/>).

Question 2: Do changes in spatial heterogeneity of burn severity vary (a) among forest types, (b) with topographic position or levels of complexity, (c) under different land management, and (d) with climate?

Ongoing work for Question 2:

This component of the project is currently underway. Completion is anticipated in December 2013.

Within-fire spatial patterns in burn severity are driven by many factors including climate, weather, topography, and fuels (Turner et al. 1994, Collins et al. 2007) and can be further affected by prior disturbances and management (Collins et al. 2009). The El Niño Southern Oscillation and Pacific Decadal Oscillation are related to inter-annual changes in the occurrence

of large fires (Schoennagel et al. 2005), but connections between climate and spatial heterogeneity of burn severity have not been examined to date. Depending on which factor(s) are most influential in generating heterogeneity, climate change in the N. Rockies may be significantly altering spatial patterns of burn severity. Current work is assessing the degree to which climate is correlated with spatial heterogeneity of burn severity, and examining changes in burn heterogeneity among different forest types, topographic contexts, and land management.

Gridded topographic information has been acquired from the USGS National Elevation Dataset (NED) at ~30 m resolution to generate topographic variables (elevation, slope, aspect, topographic complexity) for each grid cell in a fire. Forest cover-type data has been acquired from LANDFIRE (landfire.gov) at 30-m resolution. Fires are being categorized by forest type, topographic context and land-management agency (US Forest Service, National Park Service, Bureau of Land Management, private lands). I am using ANOVA to assess how changes in spatial heterogeneity of burn severity (Question 1) vary among categories. Climate data have been acquired from existing downscaled (12 km x 12 km) monthly temperature and precipitation data generated for the N. Rockies by my collaborators (Westerling et al. 2011). Each cell in the study is being assigned monthly average temperature and precipitation values. Each fire will be assigned the temperature, precipitation, and burn index (Collins et al. 2009) values (mean and 95th percentiles) from the underlying cell for a one-year time period preceding the fire, and for the duration of the fire. General linear models (with terms for spatial autocorrelation among fires) will be used to assess the relationship between climate variables and metrics of spatial heterogeneity of burn severity. Completion of this project is anticipated by December 2013.

KEY FINDINGS

Fire activity in the Northern Rockies (1984-2010)

Between 1984 and 2008, a total of 733 named forest fires larger than 200 ha occurred in the N. Rockies forests, burning 3,872,568 ha in total (Figure 3). We do not present descriptive statistics of the named fires, as each named fire in the MTBS database can represent either a single fire event or multiple fire events that were managed as a fire complex. Rather, our analysis focuses on objective delineations of severely burned area within these 733 fires.

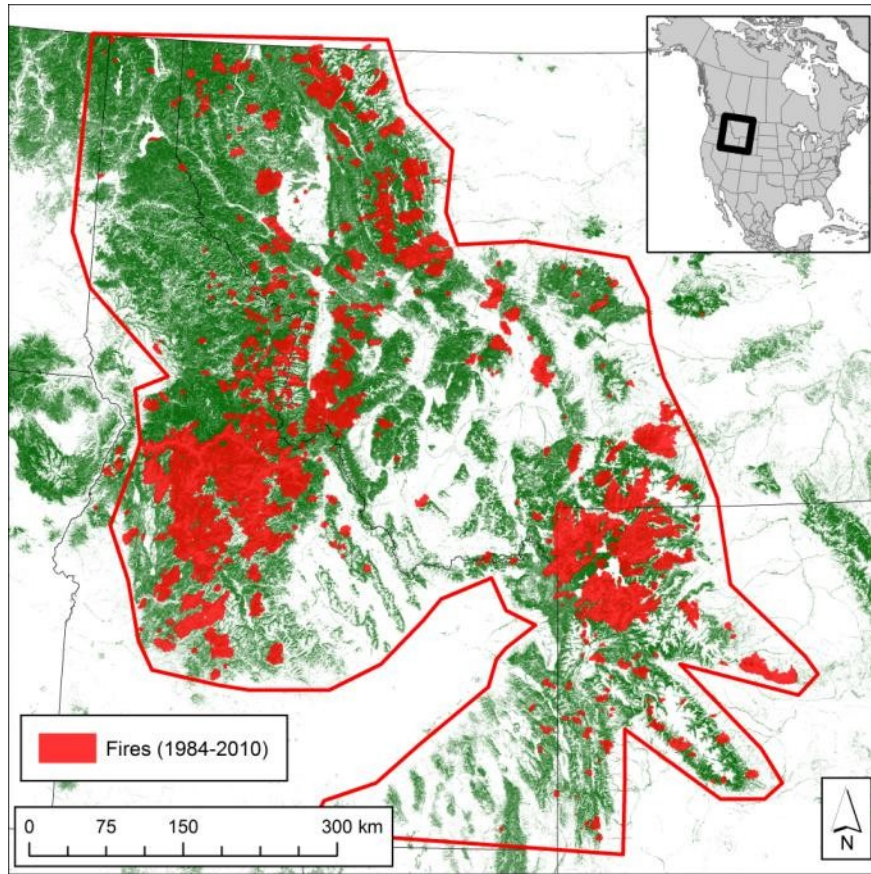


Figure 3. Study area with all forest fire perimeters included in this study (1984-2010) shaded in red.

Developing the RdNBR threshold for stand-replacing fire

Comparisons among different models used to test the relationship between pre-fire live basal area that was killed by fire and RdNBR resulted in a logistic model as the best fit (Fig. 4A). The logistic model predicted that 90% of the pre-fire live basal area was killed by fire at an RdNBR value of 702. When tested against the 185 validation plots, this model performed well (71% overall accuracy, Kappa = 0.35, Table 2). User's and producer's accuracy was > 67% for all categories except the User's accuracy of non-stand replacing fire (34%). This means that our model is if anything, slightly under-predicts stand-replacing fire. Nonetheless, accuracy values are within the range of other studies (Cansler and McKenzie 2012).

We are currently developing additional models to test the relationship between other measures of canopy (char height, bole scorching) and surface (post-fire litter + duff depth, charred surface cover) fire severity. Preliminary analysis shows promise in the utility of mapping char height with RdBNR, using an exponential model (Fig. 4B).

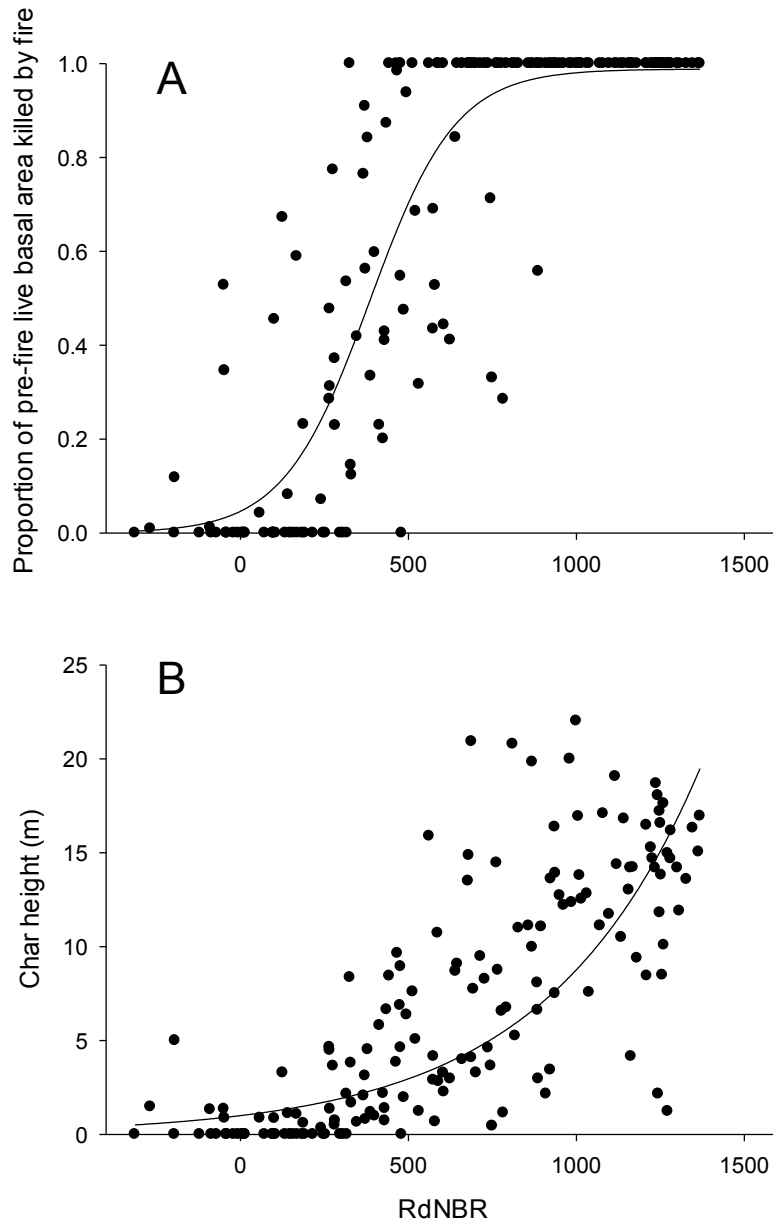


Figure 4. (A) Final logistic model used in determining threshold of stand replacing fire (> 90% pre-fire live basal area killed by fire) from RdNBR. (B) Char height and RDNBR.

Table 2. Confusion matrix and model performance for the logistic model used to map stand-replacing fire across the study area.

Predicted	Observed		User's accuracy
	Non stand-replacing	Stand-replacing	
Non stand-replacing	26	50	34%
Stand-replacing	3	106	97%
Producer's accuracy	90%	68%	

Overall accuracy = 71%, Kappa = 0.35

Amount and proportion of stand-replacing fire (1984-2010)

Of the nearly 4 million ha of forest that burned in the Northern Rockies between 1984 and 2010, 33% (1,292,587 ha) burned as stand-replacing fire (Fig. 5). The total area burned and the total area burned as stand-replacing fire fluctuate annually (Fig. 6A, B), with notable spikes in 1988, 2000, and 2007. The proportion of fires that burned as stand-replacing fire also varied annually, and ranged from 1% (1995) to 49% (2004). From 1984 to 1999, more than 30% of the burned area was stand replacing in 40% of the years; this increased to 90% of the years in the last decade (2000-2010) (Fig. 6C).

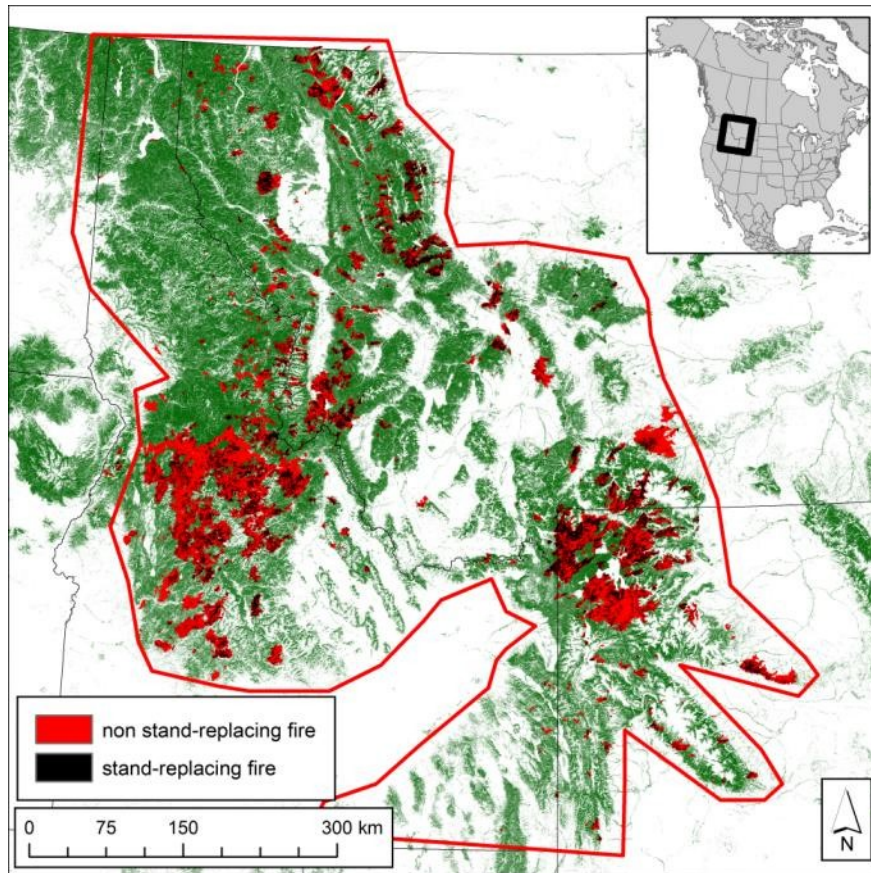


Figure 5. Study area with all forest fires for all years. Areas burned at less than stand-replacing are shown in red and areas that burned at stand-replacing are shown in black.

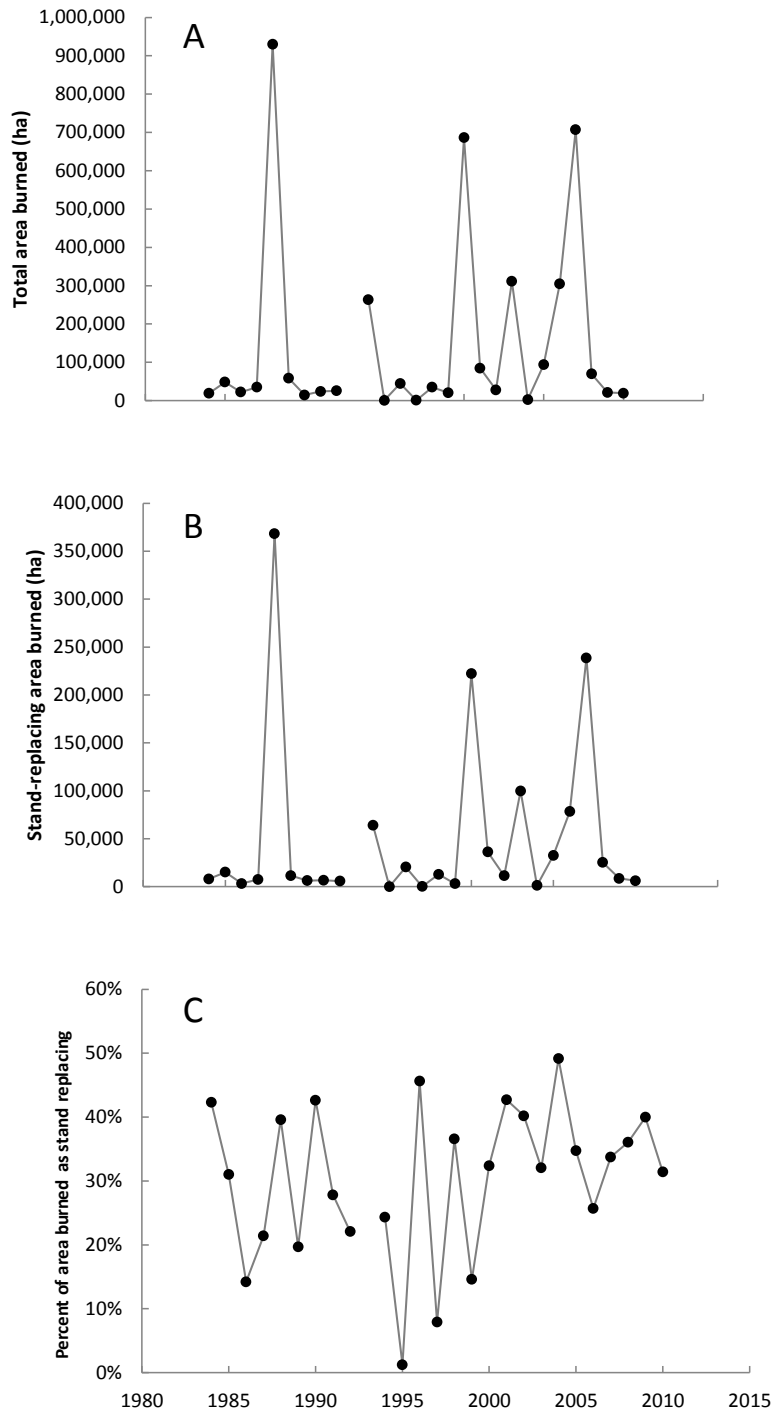


Figure 6. Total area burned overall (A) and as stand-replacing fire (B), and percentage of burned area as stand-replacing fire (C) for all forest fires (1984-2010) in the Northern Rockies, by year.

Configuration of stand-replacing fire (1984-2010)

The 1,292,587 ha that burned as stand-replacing fire between 1984 and 2010 was distributed among 173,183 individual patches. Patch size ranged from 0.09 ha (one Landsat TM

pixel) to 25,584 ha, with 75% of patches smaller than 1 ha (Fig. 7). Maximum patch size did not exceed ~2,500 ha in most years; the large fire years of 1988, 2000, and 2007 being exceptions (Fig. 8).

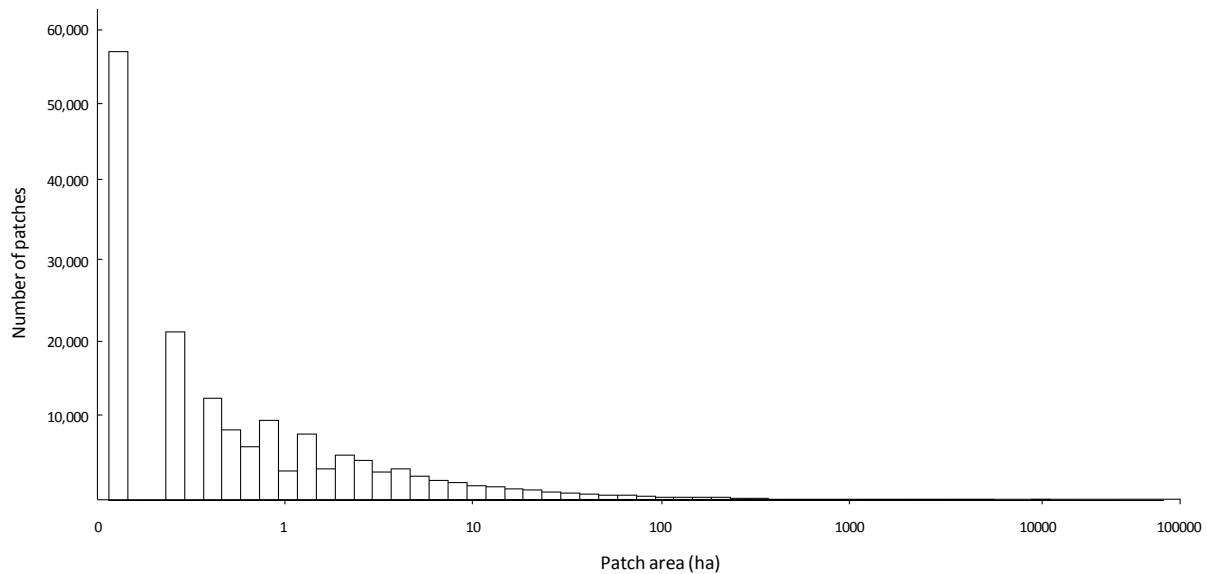


Figure 7. Frequency distribution of all patches of stand-replacing fire ($n = 173,184$) in Northern Rockies forests (1984-2010) by patch size. X-axis is log-scale.

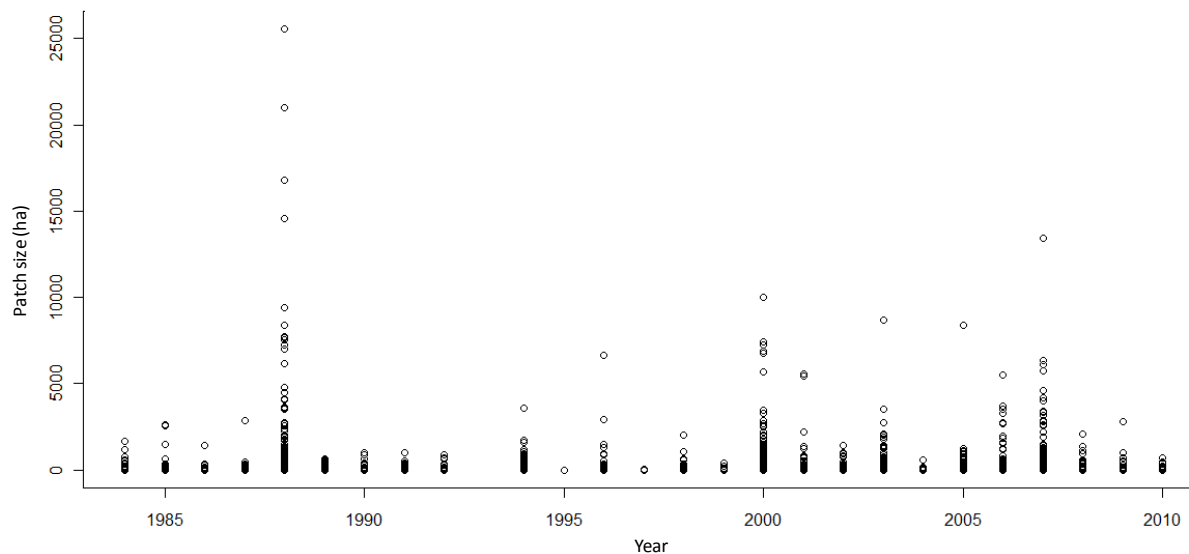


Figure 8. Patch sizes (ha) for stand-replacing fire ($n = 173,184$ patches) in Northern Rockies forests (1984-2010).

The cumulative frequency distribution for all fires across all years indicates that 50% of the total burned area occurred in patches larger/smaller than ~1,000 ha (Fig. 9A). Separate cumulative frequency distributions for each year indicated year-to-year variability in the

proportion of stand-replacing fire in small or large patches (Fig. 9B). No significant ($P > 0.05$) trend over time was apparent, as the patch size representing the 50th percentile of the total stand-replacing area burned did not change over time (Fig. 10). Mean patch size was 7.5 ha (se = 0.35), and was annually variable (Fig. 11), but showed no significant trend over time ($P > 0.05$). Yearly edge density for stand-replacing fire (m of edge per ha⁻¹ of area) also showed no significant ($P > 0.05$) trend over time (Fig. 12). Further analyses are underway to assess other metrics of the configuration of stand-replacing fire (e.g., area-weighted measures of patch size and shape).

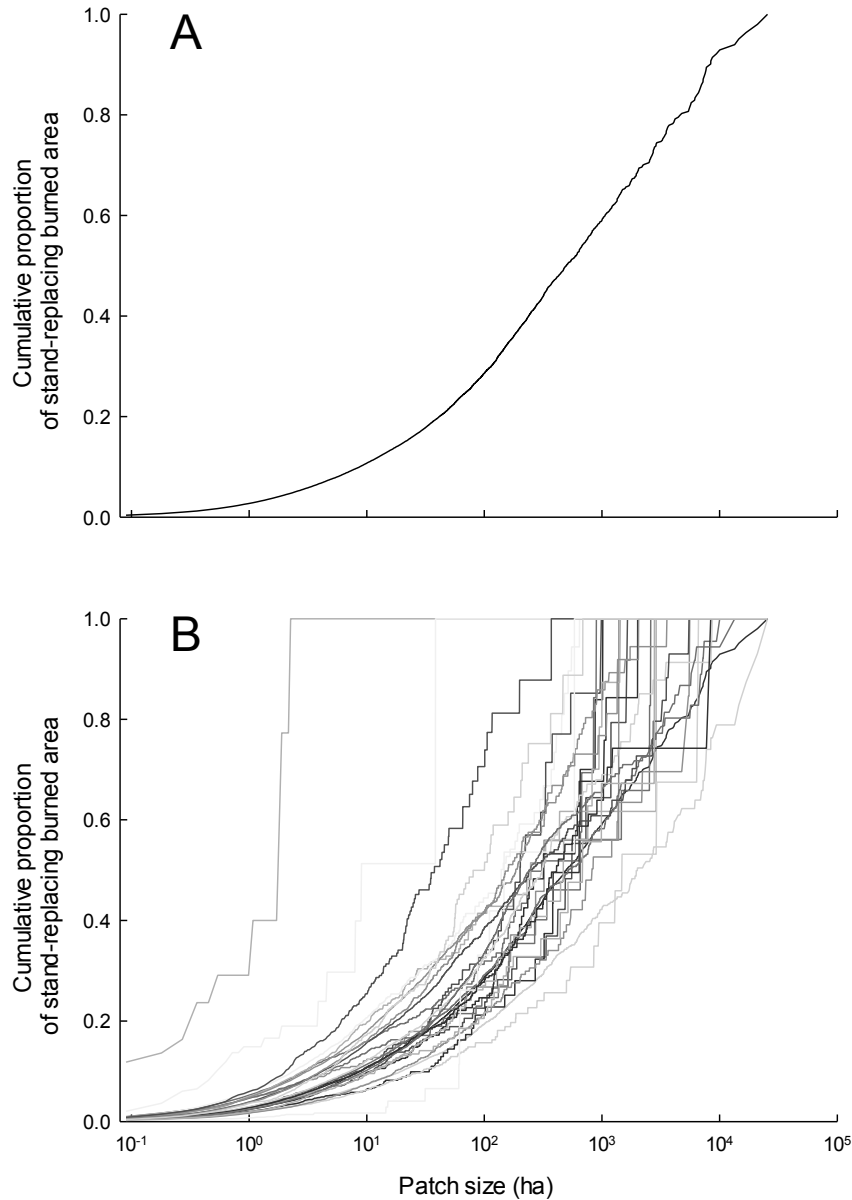


Figure 9. Cumulative frequency distribution of stand-replacing burned area (y-axis) with increasing patch size (x-axis) in all years combined (A) and in each year separately (B). Colors in (B) grade from light (1984) to dark (2010). X-axis is log-scale.

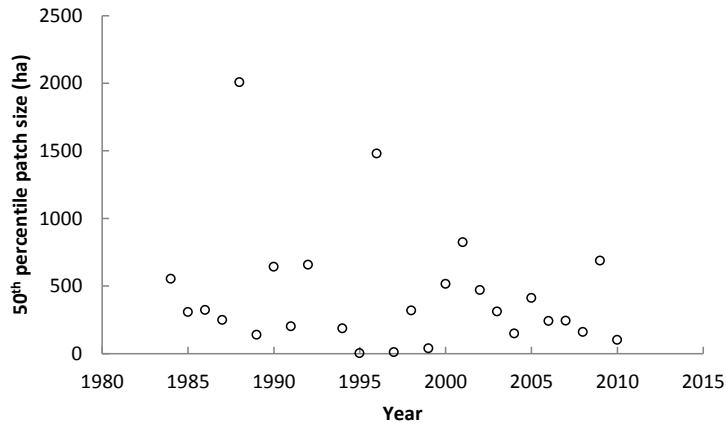


Figure 10. The 50th percentile patch size (patch size from cumulative frequency distribution at which 50% of stand-replacing area was burned, in ha) in each year. There was no significant trend over time ($P > 0.05$).

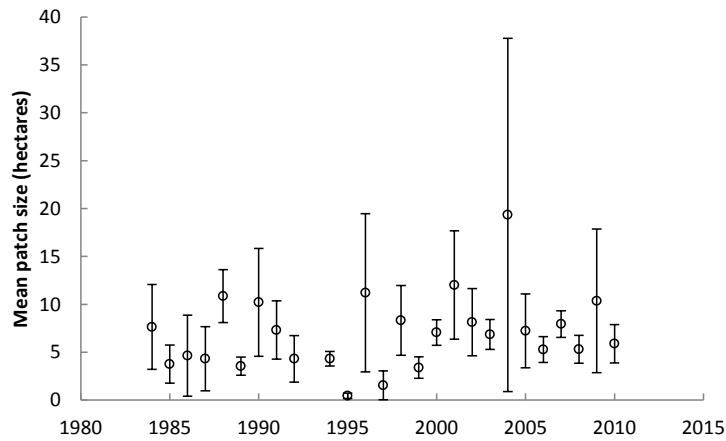


Figure 11. Mean patch size (ha) of stand-replacing fire by year. Error bars are 95% confidence intervals. No significant change over time ($P > 0.05$).

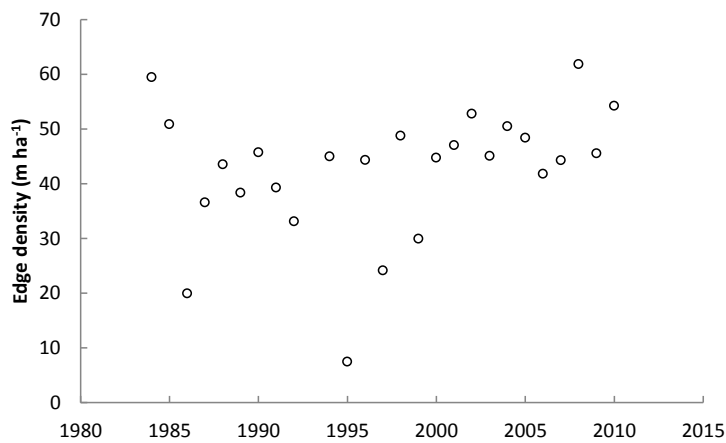


Figure 12. Edge density (m ha^{-1}) for stand-replacing fire. Edge density showed no change over time ($P > 0.05$).

MANAGEMENT IMPLICATIONS

As this work is still in progress and will be completed by December 2013, management implications are pending. However, current trends in the data can be informative to management.

First, our statistical relationship between RdNBR and field-measures of fire severity are critical for broad-scale assessments of quantitative fire effects across the Northern Rockies. While relationships between field measures and satellite measures of fire severity have been developed for other regions (e.g., Miller et al. 2009, Cansler and McKenzie 2012), information was lacking across the Northern Rockies prior to this study. With completion of additional analyses using our field data (currently underway), we will further develop relationships between other continuous measures of canopy and surface fire severity (e.g., bole scorch, surface char, post-fire litter and duff). This will be informative to managers who want to know how RdNBR translates to individual components of fire effects and can complement information collected immediately (< 1 yr) after the fire (Hudak et al. 2007).

Second, our ability to reliably map areas that burned as stand-replacing fire will help managers know where fire has killed $\sim 90\%$ of the pre-fire live basal area, as this level of pre- to post-fire change is ecologically important. It is important to remember that stand-replacing fire does not necessarily equate to negative ecological consequences, as many forest types in the Northern Rockies are adapted to stand-replacing fire through canopy seedbanks (i.e., serotiny) or wind-dispersal (Baker 2009) and average post-fire seedling densities can exceed pre-fire densities (Turner et al. 1999). However, if natural post-fire regeneration does not occur following stand-replacing fire, these areas represent potential locations where forest may transition to non-forest (i.e., savanna, shrubland, or grassland). Ongoing work is directly addressing the spatial configuration of stand-replacing fire to assess other important factors such as distance to seed source.

Early results are encouraging to managers because spatial heterogeneity of stand-replacing fire within burned perimeters has been maintained over a period of increasing fire activity. While over 1,000,000 ha have burned as stand-replacing fire since 1984, the large amount of this fire in smaller patches means that few areas across the Northern Rockies are post-fire “moonscapes.” Natural heterogeneity in burn severity is an inherent component of fire regimes, and allowing natural fires to create heterogeneity is integral to maintenance of forest ecosystem services (Turner et al. 2013). Further, management actions that can potentially homogenize burned areas (e.g., burnouts of unburned forest along edge or islands in the middle of fires) may decrease ecologically significant heterogeneity (Stephens et al. 2013).

RELATIONSHIP TO OTHER RECENT FINDINGS AND ONGOING WORK

Statistical relationships between field and satellite measures of burn severity

Rapid field-assessments of fire severity are commonly conducted using the composite burn index (CBI) method (Key and Benson 2005). While the CBI is useful for widespread characterization of fire severity, it is semi-quantitative, because observers assign an ordinal score of fire severity to several vertical strata in a plot. By quantitatively measuring canopy and surface fire severity in our plots, we are able to assign quantitative ecological meaning (e.g., % basal

area mortality, char height, surface charring) to RdNBR values. While this has been done in immediate post-fire environments (Hudak et al. 2007) and in other regions (Miller et al. 2009, Cansler and McKenzie 2012), our data can assist in mapping ground-calibrated measures of fire severity for the Northern Rockies region.

Patterns of stand-replacing fire

Our project brings a new and important perspective to research examining the recent increase in fire activity in the Western US. The availability of Landsat-derived burn severity data has led to an increase in studies examining fire severity trends in different US regions (Miller et al. 2011, Dillon et al. 2011). However, most studies have either excluded the spatial pattern of burn severity in their analyses or focused on spatial patterns in a small number of fires in a single study area (Collins and Stephens 2010). Our project allows us to track trends in these ecologically important metrics of forest condition over a wide region and time period.

Post-fire dynamics in stand-replacing patches

Stand-replacing patches of fire in a range of sizes and configurations are not outside the historical range of variability in many conifer systems in the western US (Williams and Baker 2012b, 2012a), but whether or not post-fire tree regeneration is occurring in different post-fire climates is an open question. The relationship between spatial patterns of burn severity and post-fire tree establishment has been examined in lower elevation forests of the Western US (Lentile et al. 2005, Haire and McGarigal 2008, 2010), but less is known across the higher elevation forests in the Northern Rockies. With additional funding from the National Park Service, we have initiated studies to test for tree regeneration patterns within stand-replacing patches under contrasting post-fire climates in Yellowstone, Grand Teton, and Glacier National Parks.

FUTURE WORK NEEDED

While our results so far show that spatial heterogeneity of burn severity has changed less than we expected over the period 1984-2010, continued monitoring of trends (number of fires, area burned, and spatial patterns of high-severity fire) is needed to detect potential future changes. Climate change is predicted to continue and potentially accelerate over the next several decades. Responses of burn-severity patterns to further climate changes may be non-linear, and research could prioritize identification of potential thresholds where large changes in fire patterns may occur. Modeling spatial variation in burn severity under future predicted climates may be one method to identify thresholds, and testing areas of the landscape that may be most sensitive to changes (i.e., warmer and drier locations) can validate modeled predictions. Further, our methods of explicitly testing for changes in the spatial configuration of fire severity can be applied to other regions where fire regimes may be shifting outside of the historical range of variability (e.g., southwestern drier forests).

Another future research priority is to enhance understanding of the importance of fire patterns and post-fire heterogeneity for critical ecosystem components. For example, determining the role of burn severity heterogeneity in carbon releases (e.g., from wood combustion) and carbon accrual rates (e.g., post-fire tree regeneration and growth rates) will help to inform management of timber and carbon stocks. The relationship between burn severity patterns and

the distribution of seed sources across space will be critical in determining the functional consequences of burn severity patterns. Better understanding of the responses of wildlife species to different scales of burn pattern and post-fire heterogeneity also is an important future research focus (Fontaine et al. 2009).

DELIVERABLES CROSS-WALK TABLE

Deliverables crosswalk table updated from original research proposal, with current status

Deliverable Type	Description	Delivery Dates
Refereed publication	Regional trends in spatial heterogeneity of burn severity (1984 to 2010) in the N. Rockies	In progress, December 2013
Refereed publication	Pending observed trends (Q1/Q2) 2 nd publication anticipated	In progress, June 2014
Conference presentation	Professional meeting (Association for Fire Ecology, 5 th Intl. Fire Ecology and Management Congress, Portland, OR)	Completed, December 2012
Spatial dataset	Regional maps of spatial patterns of burn severity across the N. Rockies	Completed, September 2013
PhD dissertation	Patterns and drivers of spatial heterogeneity of fire severity in the Northern Rocky Mountains, USA	In progress, May 2014

PUBLICATIONS

Harvey, B.J., Turner, M.G. In prep. Is the spatial heterogeneity of burn severity changing with warming climate and increasing wildfire? To be submitted to *Global Change Biology*.

THESES AND DISSERTATIONS

Harvey, B.J. 2014 (expected). Causes and consequences of spatial patterns of fire severity in Northern Rocky Mountain forests: the role of disturbance interactions and changing climate.

CONFERENCE PRESENTATIONS

Harvey, B.J., Turner, M.G., Donato, D.C. 2012. Spatial heterogeneity of burn severity in Northern Rocky Mountain forests (USA) between 1984 and 2011. 5th *International Fire Ecology and Management Congress*, Portland, OR. (Invited presentation in special session on “Assessing fire effects with remote sensing and geospatial technologies”).

OUTREACH TO MANAGERS

Harvey, B.J. 2013. Trends in the spatial patterns of burn severity in National Parks of the Northern Rocky Mountains (USA) between 1984 and 2010. Webinar presentation to US National Park Service managers.

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