Landscape analysis of fuel treatment longevity and effectiveness in the 2006 Tripod Complex Fires

Final Report to the Joint Fire Science Program

Project Number: 09-1-01-19
Project website:
http://www.fs.fed.us/pnw/fera/research/treatment/tripod

PRINCIPAL INVESTIGATORS:
Susan J. Prichard
University of Washington
School of Forest Resources
Box 352100
Seattle, WA 98195-2100
Telephone: (509) 996-2408
E-mail: sprich@u.washington.edu

David L. Peterson
Pacific Wildland Fire Sciences Laboratory
400 N 34th Street, Suite 201, Seattle, WA 98103
Telephone: (206) 732-7812
Facsimile: (206) 732-7801
E-mail: wild@u.washington.edu

COOPERATORS:
Travis Freed—GIS analyst, University of Washington
Rob Norheim – GIS analyst, University of Washington
Tom Leuschen – Fire Vision, LLC
Laurie Kurth – Fire & Aviation Management, NIFC

Source: firefighter photo – ftp://ftp.nifc.gov/Incident_Specific_Data/ 2006_HISTORIC/PACIFIC_NW/2006_Tripod/

FIRESCIENCE.GOV
Research Supporting Sound Decisions

Abstract

In this study, we evaluated relationships between fire severity and fuel treatment type, age and size in the 2006 Tripod Complex fires. The 2006 Tripod Complex fires, which burned over 70,000 ha and involved over 380 past harvest and fuel treatment units, offer a relatively unique opportunity to assess fuel treatment efficacy under extreme fire weather conditions. A secondary objective was to evaluate other drivers of fire severity including landform, weather, vegetation, and past disturbances including wildfires and a recent mountain pine beetle outbreak. We evaluated drivers of burn severity in two study areas that are centered on early progressions of the wildfire complex.

Predictive models of fire severity, using a differenced Normalized Burn Ratio (dNBR) as a response variable, were constructed with spatial autoregression (SAR) and ordinary least squares modeling. Significant predictor variables of dNBR include treatment type, landform (elevation and slope), fire weather (minimum relative humidity, maximum temperature and average wind for each burn progression interval), and vegetation characteristics including canopy closure and cover type. The spatial autoregressive term of the SAR models has high predictive power to identify areas of high and low severity. Classification of recent mountain pine beetle outbreak areas is a significant predictor of burn severity, but the effect on dNBR is not consistent between study areas. Treatment age and size are weak but significant predictors of burn severity. In general, burn severity increases slightly with treatment age and is reduced in larger treatment areas.

The Tripod Complex fires were one of several regional fire events in 2006. A common interpretation of weather-driven fire events is that bottom-up controls, including fuels and topography, are superseded by climatic factors and are relatively unimportant. However, even during extreme weather, landform, vegetation and fuels clearly influenced patterns of fire severity and spread in the Tripod Complex fires. Fuel treatments that included recent prescribed burning of surface fuels were particularly effective at mitigating fire severity. In contrast, units that were mechanically thinned from below and those with sanitation cuts in which small trees were cut and piled tended to burn at moderate to high severity.

Background and purpose

Under a warming climate and increased fire hazard, managers of dry forests face numerous challenges in strategizing for and implementing fuel reduction treatments. Although many types of fuel treatments are used, there have been relatively few opportunities to validate treatment efficacy in wildfires. Existing studies of fuel treatments in dry forests generally agree that mechanical thinning followed by prescribed burning is the most effective at reducing surface and crown fuels and increasing forest resilience to wildland fire (Agee and Skinner 2005, Finney et al. 2005, Strom and Fulé 2007, Reinhardt et al. 2008, Safford et al. 2009, Prichard et al. 2010, Lyons-Tinsley and Peterson *in press*). However, little is yet known about the duration of treatment effectiveness and if treatments can remain effective in extreme fire events (Agee and Skinner 2005, Peterson et al. 2005).

A promising approach to evaluating fuel treatment effectiveness at broad spatial scales is through retrospective burn severity analysis. Burn severity mapping has become standard for large fire events and in the U.S. is available from the Monitoring Trends in Burn Severity (MTBS) program (Eidenshink et al. 2007). Severity is defined as the change in reflectance between pre-burn and post-burn images. The most common image differencing technique, and the one adopted by MTBS, is the differenced Normalized Burn Ratio (dNBR). The dNBR is calculated from pre- and post-burn Landsat Thematic Mapper (TM) images and is responsive to changes in vegetation and ground reflectance (Miller and Yool 2002, Key 2006). The relative differenced Normalized Burn Ratio (RdNBR) was developed more recently to compensate for pre-fire differences between areas of high and low biomass and cover (Miller and Thode 2007, Miller et al. 2009). Comparisons of dNBR and RdNBR have shown that RdNBR may be more accurate in sparsely vegetated areas or in heterogeneous vegetation (Zhu et al. 2006, Miller and Thode 2007) whereas dNBR has been shown to more accurate in dense forests (Zhu et al. 2006, Soverel et al. 2010, Cansler and McKenzie *in review*). Availability of burn severity layers in conjunction with fire perimeter mapping, local weather data, and geospatial landform, vegetation and fuel layers makes it possible to explore the key drivers of fire severity and evaluate the effect of fuel treatments in the context of other potential covariates.

In this study, we use spatial autoregressive (SAR) and ordinary least squares (OLS) modeling to evaluate relationships between fire severity and fuel treatments and other predictor variables within the 2006 Tripod Complex fires (Fig 1). The fires, which burned over 70,000 ha with nearly 75% of the area burned at moderate to high severity, offer a relatively unique opportunity to assess fuel treatment efficacy under extreme fire weather. SAR improves on standard regression analysis by leveraging the inherent spatial autocorrelation in fire severity data to provide a proxy for missing variables, such as local fire weather and fuels (Wimberly et al. 2009).

The main objective of this study was to determine the effect of fuel treatments on fire severity across the treated portions of the Tripod Complex landscape. A secondary objective was to evaluate other factors that likely influenced the extent and severity of the wildfires including fire weather, vegetation, landform, and past disturbances. Because the Tripod was such a large event, much of the fire spanned untreated landscapes in which forest and fuels management had little or no influence on fire spread and severity. We were particularly interested in evaluating whether a recent, mountain pine beetle (MPB) and spruce beetle (*D. rufipennis*) outbreak influenced patterns of fire severity across the post-fire landscape.

Study location and description

Study area

The Tripod Complex is located in the Okanogan-Wenatchee National Forest, north central Washington State (Fig 1) and was the largest wildfire event in Washington State in over 50 years. The wildfires were preceded by an early spring snowmelt and an ongoing MPB and spruce beetle outbreak in mid- to high-elevation forests. The fires initiated as two separate lightning strikes. The Spur fire ignited on July 4th, 2006 and was fully contained by July 12th. The Tripod fire started on July 24th. Under strong gusty winds and extreme fire weather, the Spur fire jumped containment lines, and both fires spread rapidly as a mixture of crown fires and high-intensity surface fires. The fires converged in mid-August and were extinguished in late October by a season-ending snowfall. The fires burned 387 harvest and prescribed burn units dating back to the early 1970s. Past harvests include clearcut, shelterwood, and commercial thinning projects, located mostly in low to mid-elevation forests. Harvests that occurred before the mid 1990's generally were conducted for reasons other than treating hazardous fuel (e.g., extracting merchantable timber and forest type conversion), but many units were broadcast burned or underburned following harvest to reduce logging slash.

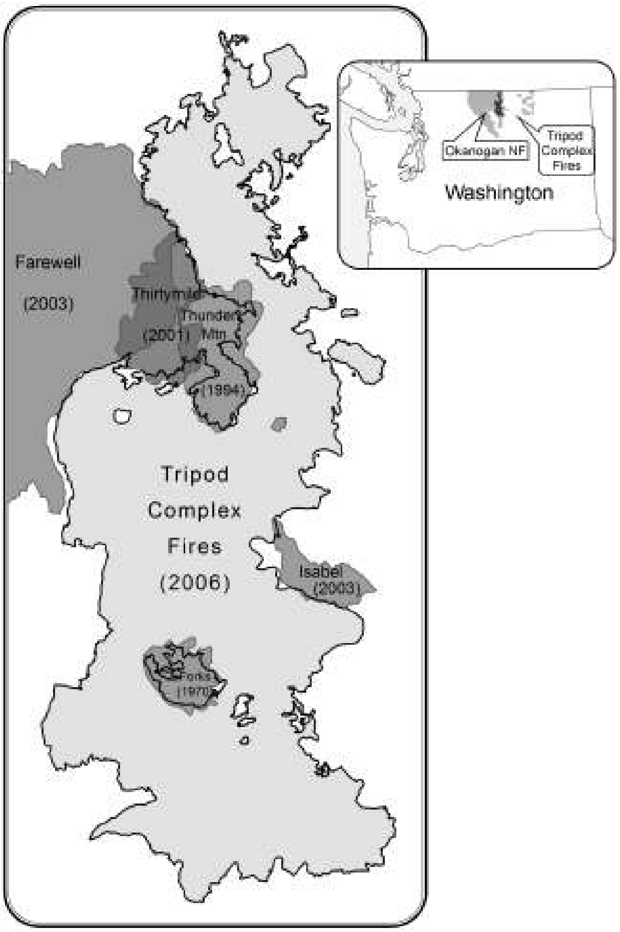

Figure 1: Location of Tripod Complex Fires and recent wildfires.

Fire severity images and field validation

Differenced normalized burn ratio (dNBR) and RdNBR images used in this analysis were calculated based on virtually cloud-free, pre-and post-burn Landsat TM images taken one year prior to and one year following the 2006 Tripod Complex fires (Monitoring Trends in Burn Severity assessment of Fire Information: FS-0617-010-20060703 http://mtbs.gov/dataquery/individualfiredata.html). Fire severity was classified into four classes: unchanged, low, moderate, and high severity using standard procedures from Key (2006)(Fig 2).

Composite burn index (CBI) data were collected to validate that dNBR and RdNBR represented burn severity in the field and to compare the two indices. Validation plots (Key 2006) were sampled across a range of severity classes during the summers of 2007 and 2009. A total of 44 plots were collected in the summer of 2007 as part of a study by Newcomer et al. (2008). We supplemented this dataset with an additional 55 plots in the summer of 2009 to ensure adequate representation in each burn severity class. Needles on scorched trees were still present in 2009 and allowed for comparable CBI observations.

Predictive data layers

Prior to analysis, we assembled data layers of predictor variables summarized in Table 1. A geospatial treatment layer, including harvest type and date and prescribed burn type and date, was compiled within the Tripod Complex perimeter and verified using hard-copy records. Landform variables were derived from a 30-m digital elevation model. Existing vegetation type (cover type) and canopy cover (CC, %) layers were obtained from LANDFIRE (LANDFIRE 2011). LANDFIRE existing vegetation types were reclassified into major cover types: alpine (Alp), avalanche chute (AV), dry mixed conifer (DMC), Engelmann spruce-subalpine fir (ESSF), Grass, lodgepole pine (LP), ponderosa pine (PP), riparian forest (Rip), Shrub, and subalpine forest (Subalp).

Fire perimeter maps were obtained from the National Interagency Fire Center (http://www.nifc.gov) and used to compile a progression layer with weather data summarized and assigned by progression interval (Fig 3). Where possible, available IR imagery and Landsat TM images captured during the Tripod Complex fires were used to verify and correct fire perimeters. Daily weather records were obtained from the First Butte Remote Automated Weather Station (RAWS) station, located near the western edge of the Tripod Complex perimeter (Fig 2), and summarized by fire interval (Table 1).

Forests under red-attack by MPB (defined as recently attacked trees with red crowns) were classified from Landsat 5 TM imagery from August 18, 2003 to August 8, 2005 using the enhanced wetness difference index (EWDI, Wulder et al. 2006). EWDI values were classified into the following categories after Wulder et al. (2006): regeneration including old clearcut blocks (Regen, < -7), healthy (Green, -7 to 2), healthy to red attack (Mixed, 2 to 7), red attack (Red, 7 to 18), and red attack with foliage loss (Red-Gray, > 18).

Data analysis

SAR and OLS models were constructed in the R programming language (Wimberly et al. 2009, R Development Core Team 2011) to predict fire severity based on the following layers: progression order (ProgOrd); landform variables including elevation (Elev, m), slope (Slop, %), and heat load index (heat load); weather variables including MaxTemp, MinRH, AvgWind, and MaxGust; vegetation variables including Cover Type and CanCov, EWDI, MPB classification; and past fuel treatment including recent wildfires (Table 1). Treatment contrasts were assigned to all categorical variables, including fuel treatment (base = no treatment, NT), cover type (base = DMC), and MPB classification (base = Green). Box and whisker plots were used to examine relationships between predictor variables and dNBR. Simple OLS models were included in the analysis to evaluate differences in predictive power and model parameters between the two approaches.

Table 1: Predictor variables used in OLS and SAR modeling. Base contrasts used for statistical comparison of categorical variables are indicated by an asterisk (*).

Variable	**Definition**
FUEL TREATMENT	
Age (yr)	Years since harvest date, prescribed burn, or wildfire
Size (ha)	Treatment area
Treatment category	Untreated (NT)*
	Clearcut (CC)
	Clearcut and broadcast burn (BB)
	Landscape burn (LB)
	Salvage harvest (Salv)
	Thin only (Thin)
	Thin and broadcast burn (ThinBB)
	Thin and sanitation cut (ThinSan)
	Past wildfire (WF, since 1980)
LANDFORM	
Elev (m)	Elevation
Slope (°)	Slope gradient
Heat load index	Calculated Beers (1966) heat load index, used as a proxy for aspect
WEATHER	
MaxTemp (°C)	Maximum temperature over each fire progression interval
MinRH (%)	Minimum relative humidity each fire progression interval
MaxWind (kph)	Maximum recorded wind gust over each fire progression interval
AvgWind (kph)	Average wind speed over each fire progression interval
VEGETATION	
CanCov (%)	Percent ground cover of vegetation (LANDFIRE)
Cover type	Existing vegetation type (LANDFIRE)
EWDI	Enhanced wetness difference index
Mountain pine beetle (MPB) classification	Regeneration (Regen)
	Healthy, green (Green)*
	Green and red (Mixed)
	Red-attack (Red)

We selected dNBR as the response variable in all models because this index is considered more appropriate for changes in forest cover and biomass than RdNBR (Zhu et al. 2006, Miller and Thode 2007); dNBR distributions tend to be more normally distributed than RdNBR values; and dNBR and RdNBR have been demonstrated to have similar accuracy in the northern Cascades (Cansler and McKenzie *in review*). Models were compared using Akaike's information criterion (AIC), and final models were selected to include only significant covariates ($\alpha = 0.05$) and the lowest AIC values.

For the SAR analysis, it was necessary to reduce the size of our dataset to fewer than 100,000 observations (Kazar et al. 2004, Wimberly et al. 2009). We selected two subareas of the Tripod Complex fires that contain the majority of fuel treatments and represent the early stages of the wildfires when the Spur and Tripod fires were separate fire events (Fig 2). Using two study areas allowed us to compare findings in co-occurring fires burning in similar vegetation types but with a different set of fuel treatment types and landscape configuration

(Fig 3). From the original 30-m resolution data layers, pixels were resampled to a 60-m by 60-m sampling grid, centered on each pixel (Wimberly et al. 2009).

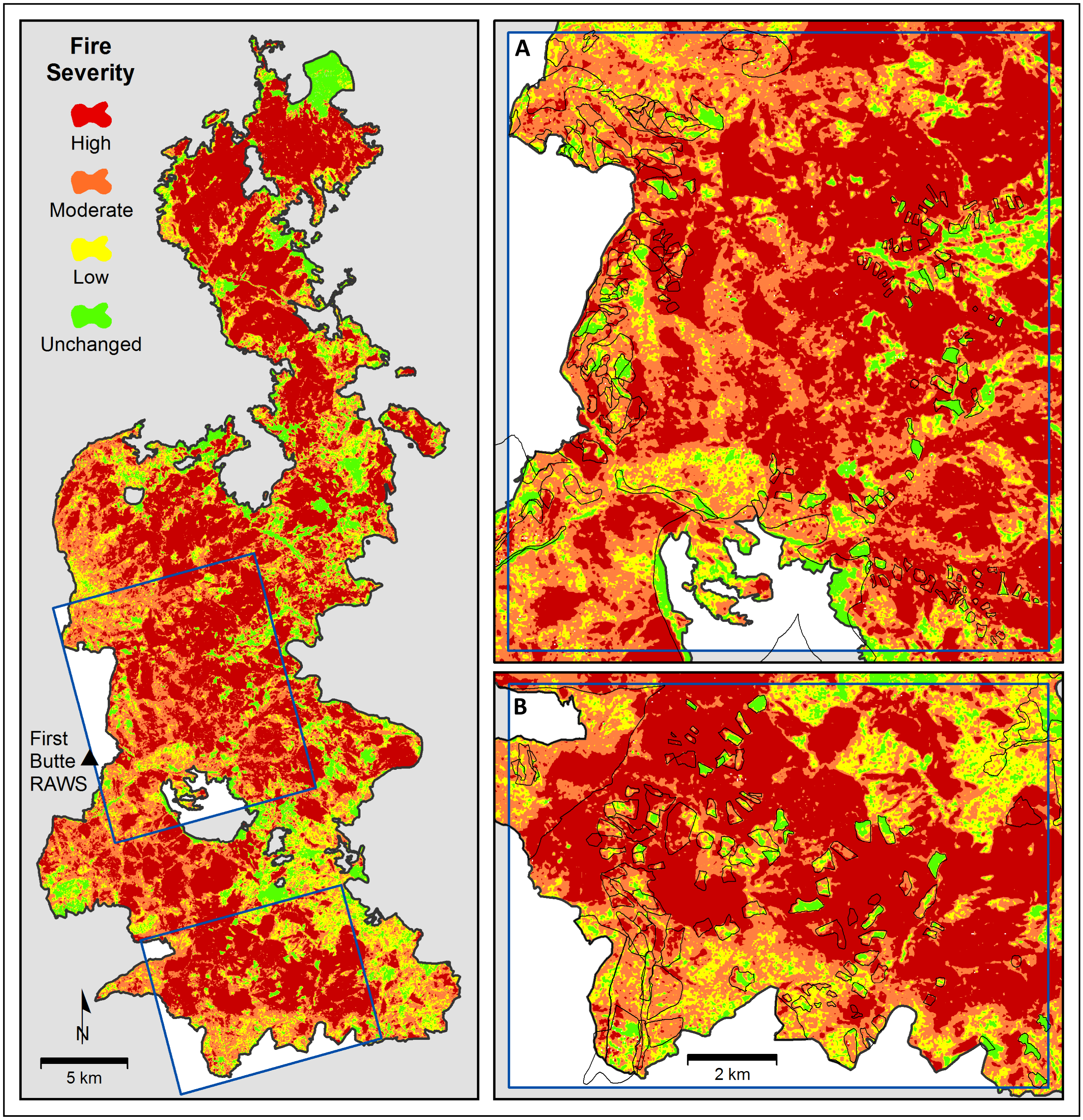

Figure 2: Burned area reflectance classification image of the Tripod Complex fires with the Spur (north) and Tripod (south) sampling areas. Spur (A) and Tripod (B) study areas are displayed on the right with fuel treatments outlined in black.

Because untreated pixels had no assignment of time since treatment or treatment area, a separate analysis was necessary to evaluate the effects of treatment age and size. We confined our dataset to treated portions of the Tripod landscape and randomly sampled 2000 pixels by major treatment type (CC, CCBB, Thin, ThinBB, and WF). Random sampling of data points was performed to emulate a high-intensity field study and remove spatial autocorrelation, an important criterion for linear regression modeling. Treatment edges were excluded from the sample using a 60-m buffer within each treatment perimeter. Simple linear regression models were constructed by major treatment type to predict dNBR based on time since treatment (Age, years), Size (ha), and continuous variables found to be important predictors in the SAR models, including CC, Elev, Slope, EWDI, MaxTemp, and AvgWind. Final model selection was based on the significance of predictor variables and the lowest AIC values.

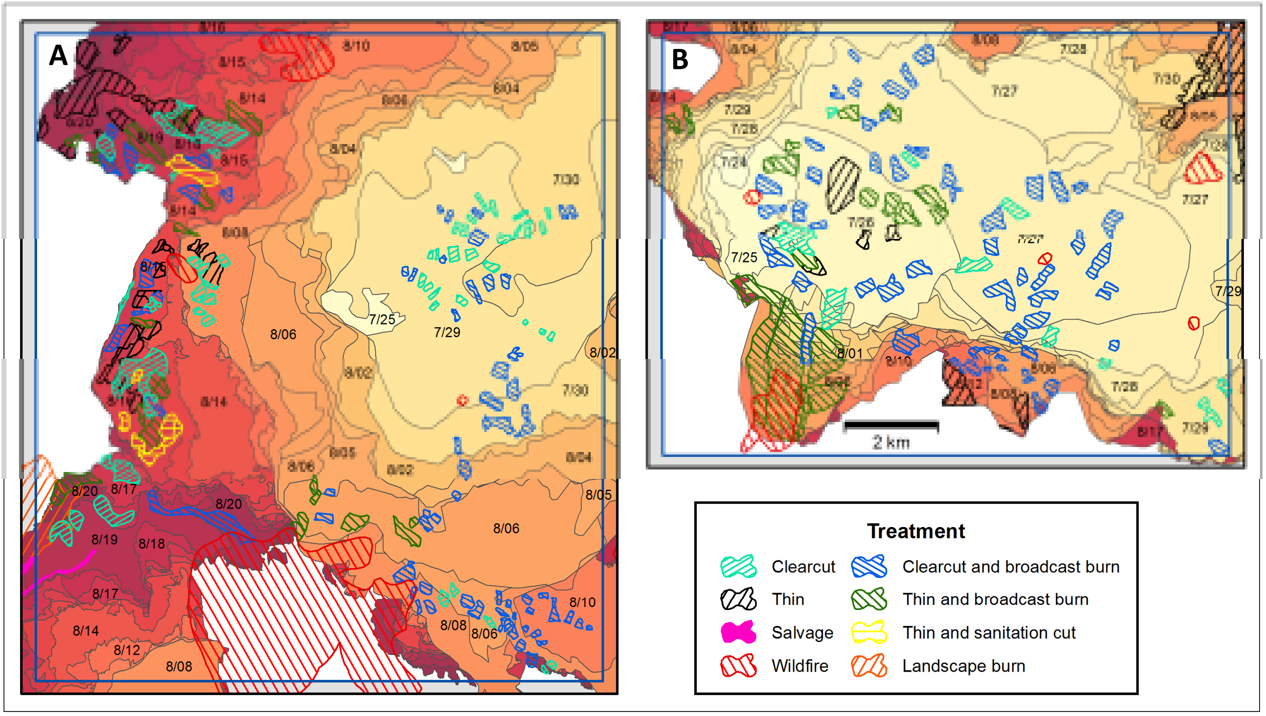

Figure 3: Fire progression intervals and treatment polygons in the A) Spur and B) Tripod study areas.

Key findings

1. Fuel treatments and past wildfires mitigated fire severity under extreme fire weather

The Tripod Complex fires were one of several regional fire events in 2006. The 2006 fire season represents the largest area burned since 1984 in the northern Cascades (Cansler and McKenzie *in review*) and second largest recorded area burned since 1980 across the broader eastern Cascade region (Littell and Gwozdz 2011). Regional fire years generally correspond to higher than average spring and summer temperatures and drier than average summers (Gedalof et al. 2005, Morgan et al. 2008, Littell et al. 2009). In the Pacific Northwest, most fires tend to burn at mid- to high elevations during regional fire years (Heyerdahl et al. 2008). As part of regional fire seasons, large fire events such as that of the Tripod Complex fires are generally characterized by top-down climatic controls (e.g., large frontal systems accompanied by high temperatures, dry air and strong winds)(Littell and Gwozdz 2011). A common interpretation of weather-driven fire events is that bottom-up controls, including fuels and topography, are superseded by climatic factors and are relatively unimportant (Turner and Romme 1994, Bessie and Johnson 1995).

Even under extreme fire weather, vegetation and fuels clearly influenced patterns of fire severity and spread. The majority of the fire burned at mid-to high-elevations, concentrated in lodgepole pine and Engelmann spruce forests, and over 73% of the burned area was classified at moderate to high severity. Past wildfires still had a strong influence on the patterns of fire spread, likely due to a lack of available surface fuels for fire spread. Recent fires, including the 1994 Thunder Mountain fire, 2001 Thirty-mile fire, and 2003 Farewell and Isabel fires, constrained fire spread (Fig 1); the Tripod Complex fires wrapped around the edges of these regenerating landscapes with little overlap in area burned. A somewhat surprising fire break was the 1700-ha 1970 Forks fire, composed of regenerating, 40-year-old lodgepole pine forest with sparse surface fuels. The effect of past wildfires on fire severity was not uniform. Older wildfires, particularly in the Tripod study area, burned at moderate to high severity, whereas more recent fires in the Spur study area burned at a low severity.

Many prescribed burn units now comprise islands of mature and regenerating trees in a landscape otherwise highly modified by stand-replacing fire (Fig 2). As the wildfires burned through the treated portion of the landscape, observed fire behavior included spotting distances of 0.5 to 1 km (Matt Castle, fire behavior analyst, Washington Department of Natural Resources), and the fires often burned at high severity within the unmanaged matrix around treatment blocks. The effects of fuel treatments appear localized with no evident protection of leeward, neighboring pixels as described by Finney et al. (2005) in the 2002 Rodeo-Chedeski fires (Fig 2).

Fuel treatments that received prescribed burning of surface fuels have lower dNBR values than other treatments (Fig 4). In contrast, thin-only and thin and sanitation treatments generally burned at moderate to high severity and are not significantly different than untreated forests. Due to increased surface fuel loads, thin-only treatments may actually pose a higher fire risk if not treated with prescribed fire (Agee and Skinner 2005, Reinhardt et al. 2008). Inclusion of treatment categories results in a substantial reduction in SAR model AIC values, and most treatments are significantly different than no treatment (NT), which was assigned as the base contrast (Table 2). In both study areas, the clearcut and prescribed burn treatment has the greatest difference from the NT base contrast, and all prescribed burn treatments have lower dNBR values than treatments without prescribed fire. Our findings are corroborated by two previous field studies in the Tripod Complex fires conducted in thin and prescribed burn units (Prichard et al. 2010) and young, regenerating stands (Lyons-Tinsley and Peterson 2011). Both studies demonstrate that units that were prescribed burned prior to the Tripod Complex fires had significantly lower tree mortality and other fire severity measures (e.g., crown scorch and bole char height) than thin or clear-cut only treatments.

Table 2: Predictor variables, coefficients, standard error (SE) and P values in the SAR models. CC = clearcut, CCBB = clearcut and broadcast burn, LB = landscape burn, Salv = salvage, Thin = thin only, ThinBB = thin and broadcast burn, ThinSan = thin and sanitation cut, WF = wildfire, AV = avalanche, DMC = dry mixed conifer, ESSF = Engelmann spruce/subalpine fir, LP = lodgepole pine, MC = mixed conifer, NV = nonvegetated, PP = ponderosa pine, Rip = riparian, Subalp = subalpine. Positive treatment coefficients imply greater fire severity and negative coefficients imply lower fire severity compared to baseline contrasts (Treatment = no treatment, MPB = Green, and Cover type = dry mixed conifer). Unused predictor variables are indicated by "na".

	SPUR FIRE			**TRIPOD FIRE**		
Variables	Coefficient	SE	P	Coefficient	SE	P
(Intercept)	27.33	41.82	0.5133	-49.98	88.04	0.5702
Treatment_CC	-65.81	7.70	< 0.0001	-96.93	13.34	0.0000
Treatment_CCBB	-96.48	7.19	< 0.0001	-126.75	7.00	< 0.0001
Treatment_LB	-57.17	28.86	0.0476	na	na	na
Treatment_Salv	23.70	31.54	0.4521	na	na	na
Treatment_Thin	-35.09	9.84	0.0004	-43.50	14.36	0.0025
Treatment_ThinBB	-77.32	10.10	< 0.0001	-61.50	10.72	< 0.0001
Treatment_ThinSan	-56.20	18.86	0.0029	na	na	na
Treatment_WF	-31.69	12.44	0.0108	54.90	24.09	0.0227
Elev (m)	0.22	0.05	< 0.0001	0.22	0.05	< 0.0001
Slope (%)	0.58	0.25	0.0195	0.55	0.25	0.0208
CanCov (%)	1.59	0.07	< 0.0001	1.60	0.07	< 0.0001
Mpb_mixed	3.08	1.73	0.0743	-8.95	2.17	< 0.0001
Mpb_red	-8.20	3.34	0.0142	-17.49	6.42	0.0065
Mpb_regen	-32.13	5.03	< 0.0001	-22.90	7.29	0.0017
AvgWind (kph)	2.26	1.04	0.0305	2.65	1.12	0.0181
MaxTemp (°C)	na	na	na	2.34	0.68	0.0006
Cover_Alp	29.24	5.83	< 0.0001	36.64	7.17	< 0.0001
Cover_AV	15.68	10.47	0.1344	73.49	13.69	< 0.0001
Cover_ESSF	2.63	2.69	0.3283	-2.95	2.88	0.3066
Cover_Grass	22.51	4.66	< 0.0001	34.50	5.71	< 0.0001
Cover_LP	5.80	3.19	0.0695	1.58	3.61	0.6604
Cover_PP	3.47	5.86	0.5542	28.28	13.16	0.0316
Cover_Rip	-41.10	6.21	< 0.0001	-47.75	12.35	0.0001
Cover_Shrub	3.99	7.72	0.6056	20.18	11.27	0.0735
Cover_Subalp	-1.38	3.50	0.6931	17.89	6.59	0.0066

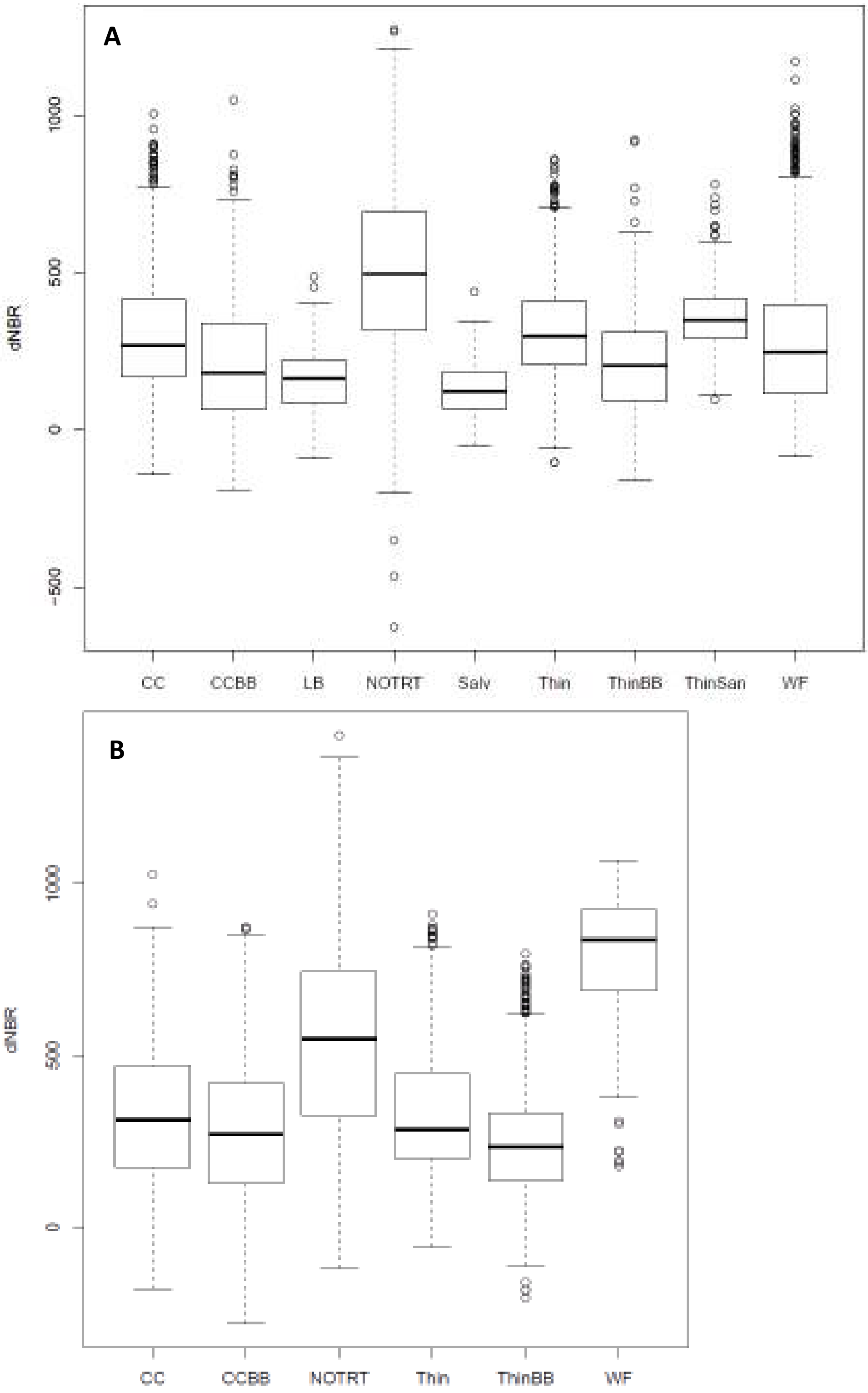

Figure 4: Box and whisker plots of dNBR by treatment category in the A) Spur and B) Tripod study area. Boxes represent the most common dNBR values between 25 and 75 percent with a 50 percent median line. Whiskers represent minimum and maximum dNBR values, and outliers are indicated by circles. Treatments include: clearcut (CC), clearcut and broadcast burn (CCBB), landscape burn (LB), no treatment (NOTRT), salvage (Salv), thin-only (Thin), thin and broadcast burn (ThinBB), thin and sanitation cut (ThinSan), and wildfire (WF).

2. Drivers of fire severity – examination of landform, weather, and fuels

Our ability to predict fire severity is limited by a number of missing variables that are generally unavailable for large fire events (Finney et al. 2005, Collins et al. 2007, Wimberly et al. 2009). These include vegetation structure; surface fuel loads and moistures; local fire weather including wind speed, wind direction, temperature and relative humidity; and fine-scale interactions between topography, fuels, wind and fire. We approached the missing variable problem by assigning hourly weather from a nearby weather station by progression interval and the SAR modeling approach. The SAR models offer a substantial refinement to traditional regression models by using the inherent spatial autocorrelation of pixels as a proxy for the missing variables (Wimberly et al. 2009).

Predicted dNBR values using the SAR modeling approach have strong correspondence to actual dNBR values; spatial patterns of low and high severity are visibly similar between actual and predicted values (Fig 5, 6). The autoregressive term is particularly good at predicting areas of high severity, likely reflecting that high severity crown fire events spread as a contagious process, with neighboring unburned areas more likely to burn if adjacent cells have burned at high severity (Peterson 2002). Significant predictor variables are similar between both study areas and include treatment type, Elev, Slope, MaxTemp, AvgWind, CanCov, cover type, and MPBclass (Table 3). Variables tested that are not significant predictors in any model include heat load index and MaxWind. Progression order contributes to lower OLS model AICs in the Tripod study area but is not a strong predictor in the Spur study area.

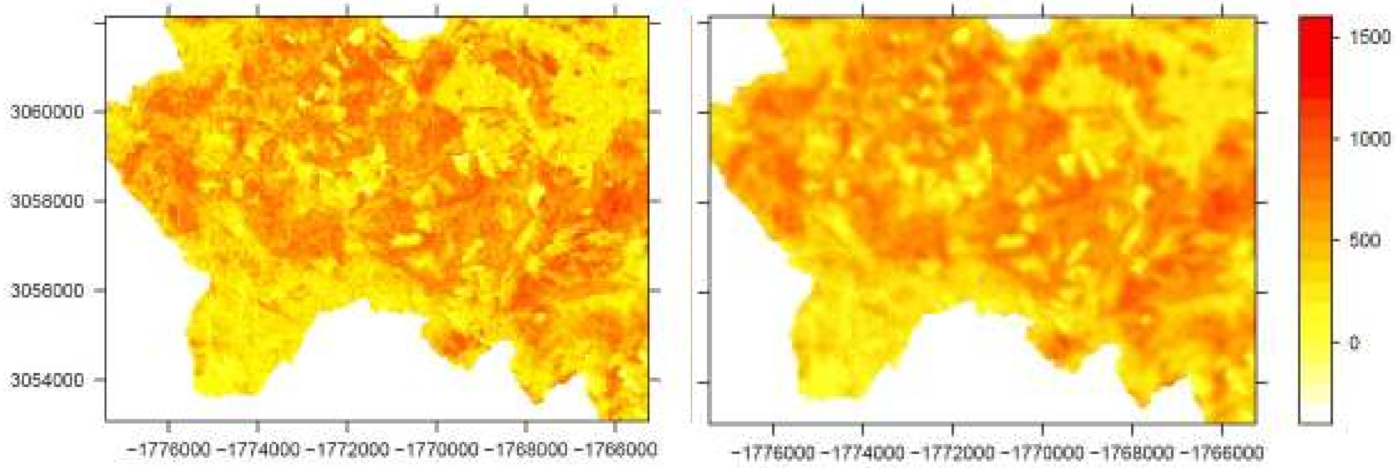

Figure 5: Actual dNBR values (A) vs. predicted dNBR values from the SAR model w/ fire progression for the Tripod study area.

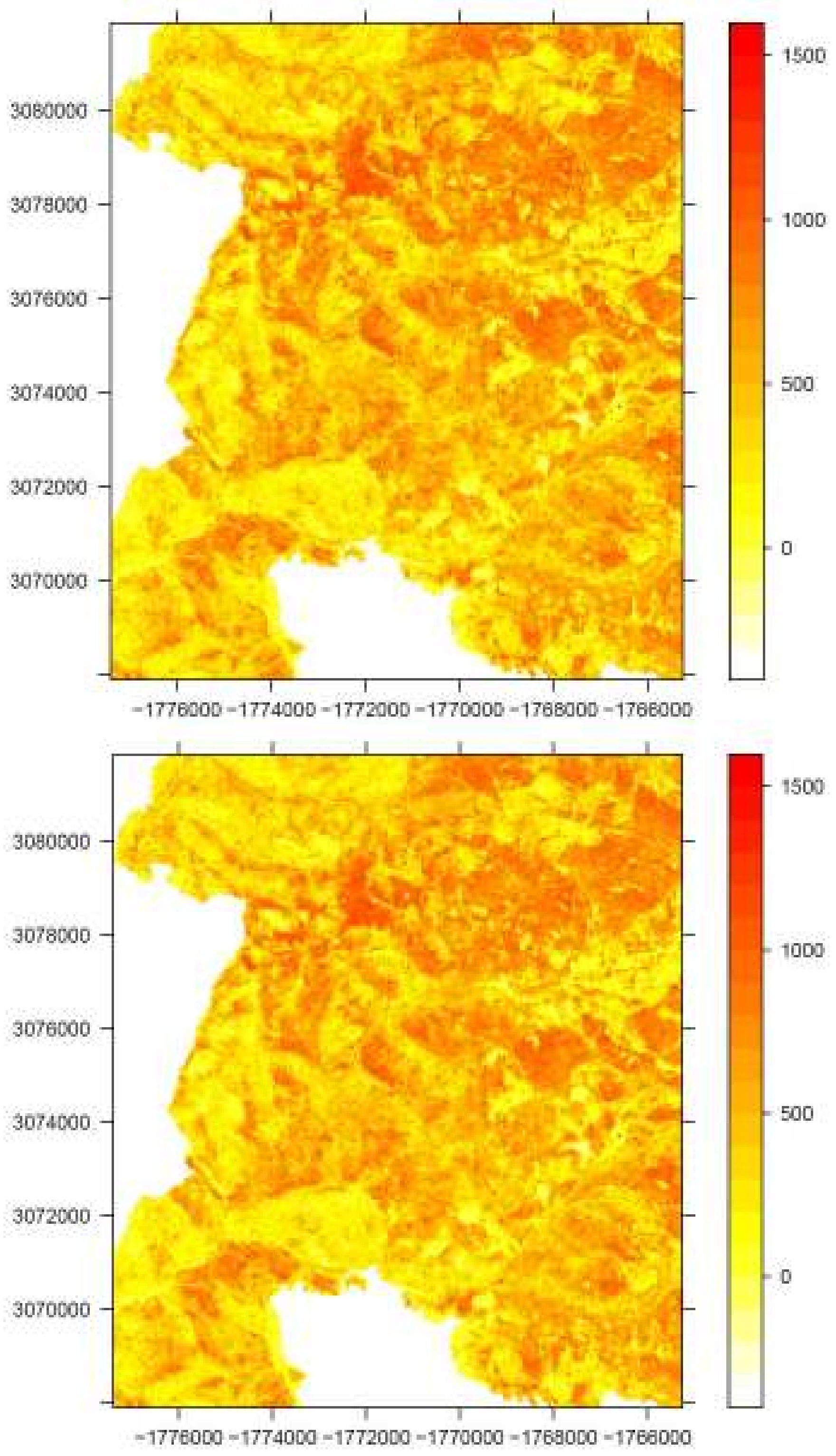

Figure 6: Actual dNBR values (A) vs. predicted dNBR values from the SAR model w/ fire progression for the Tripod study area.

Table 3: Predictive models of dNBR. The alpha level of all models is 0.05. N = sample size, R^2 = coefficient of determination, and AIC = Akaike's information criterion.

Model	Predictor variables	N	R^2	AIC
Spur_OLS	Treatment, Elev, Slope, CanCov, MaxTemp, AvgWind, MPB, Cover type	40506	0.2896	548417
Spur_OLS_prog	Treatment, Elev, Slope, CanCov, MPB , Cover type, Progression order	40506	0.3156	546944
Spur_SAR	Treatment, Elev, Slope, CanCov, AvgWind, MPB, Cover type	40506	0.7298	516224
Tripod_OLS	Treatment, Elev, Slope, CanCov, MaxTemp, AvgWind, MPB, Cover type	25267	0.3726	317796
Tripod_OLS_prog	Treatment, Elev, Slope, CanCov, MPB, Cover type, Progression order	25267	0.4265	315708
Tripod_SAR	Treatment, Elev, Slope, CanCov, MaxTemp, AvgWind, MPB, Cover type	25267	0.7820	297218

The following sections address the relative contributions of landform, weather variables and vegetation, and fuels to predicting fire severity across the Tripod Complex landscape. Modeling fire severity in two study areas that burned around the same time period allowed us to determine if our results were broadly applicable to similar forest types or if results might be an artifact of our particular sampling area (i.e., past wildfires in the Tripod study area).

3. *Landform*

Fire severity, as represented by dNBR values, is highest at mid- to high-elevations between 1500 and 2000 m in both study areas (Fig 7, 8). The relationship between elevation and fire severity is understandable given that low elevations (< 1000 m) tend to support more fire resistant species such as Douglas-fir and ponderosa pine and mid elevations tend to be denser mixed conifer stands that are more susceptible to high-severity fire events (Agee 1993). At the highest elevations (> 2000m), forest vegetation consists of subalpine parklands and alpine grasslands which generally remained unburned or burned at low severity.

There is no significant relationship between heat load index and fire severity. Slope gradient is only weakly correlated with dNBR (Table 2). Mean dNBR values are actually lower at higher slope gradients. Although fire behavior is typically greater on higher slope gradients, steep topography can also limit fire behavior by creating flank and backing fires (Johnson and Miyanishi 2001).

4. *Weather*

Because we assigned weather variables (MaxTemp, MinRH, AvgWind, and MaxWind) by progression interval from a remote weather station, we anticipated that relationships with fire severity would be weak. However, MaxTemp and AvgWind are important predictors in some models, suggesting that broadly summarized weather by progression interval was still able to represent finer-scale fire-weather relationships (Table 2). Collins et al. (2007) also report significant relationships between weather assigned by progression interval and fire severity. Accuracy and consistency of progression intervals were important to this analysis. The Tripod study area contains fewer progressions than the Spur study area and also has ample IR imagery to validate each progression interval. The Spur study area spans the initial early July progression along with later July and August progressions in common with the Tripod fire. Because fire perimeters are numerous and tend to be complex in the Spur fire, it is reasonable that weather variables assigned by progression intervals were not strong predictors of fire severity within this study area.

5. Vegetation

Vegetation cover and type are both important predictors of burn severity (Table 2). Canopy cover is highly correlated with dNBR with higher burn severity at higher canopy cover values (Fig 7, 8). As a change detection index, dNBR is sensitive to large changes in reflectance, (e.g., stand-replacing fire events in dense forest types), so the relationship between canopy cover and burn severity would be expected to be strong. Fire severity is also highest in higher elevation forest types (ESSF, LP, MC, and Subalp), which tend to grow densely with multilayered canopies and are more structurally predisposed to stand-replacing fire (Agee 1993). Low elevation vegetation (e.g., Grass, PP, and Shrubs) generally have low dNBR values and are not strong predictors of fire severity. Alp, AV and Rip cover types have low dNBR values, likely due to high site moisture in each case.

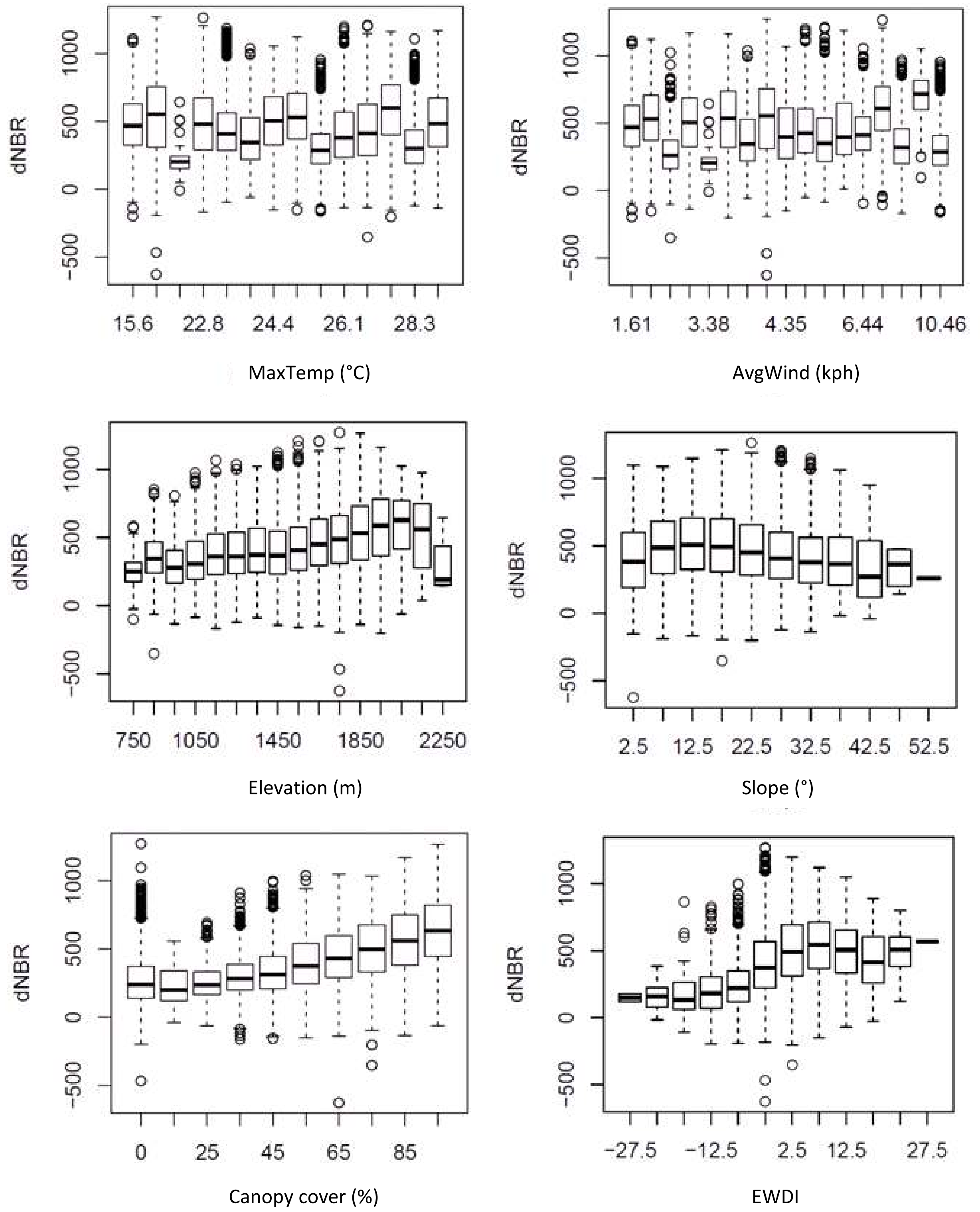

Figure 7: Box and whisker plots between dNBR and 6 predictor variables in the Spur Fire. Individual box plots summarize dNBR values for binned values of each continuous predictor variable. Boxes represent the most common dNBR values between 25 and 75 percent with a 50 percent median line. Whiskers represent the minimum and maximum dNBR values, and outliers are indicated by circles.

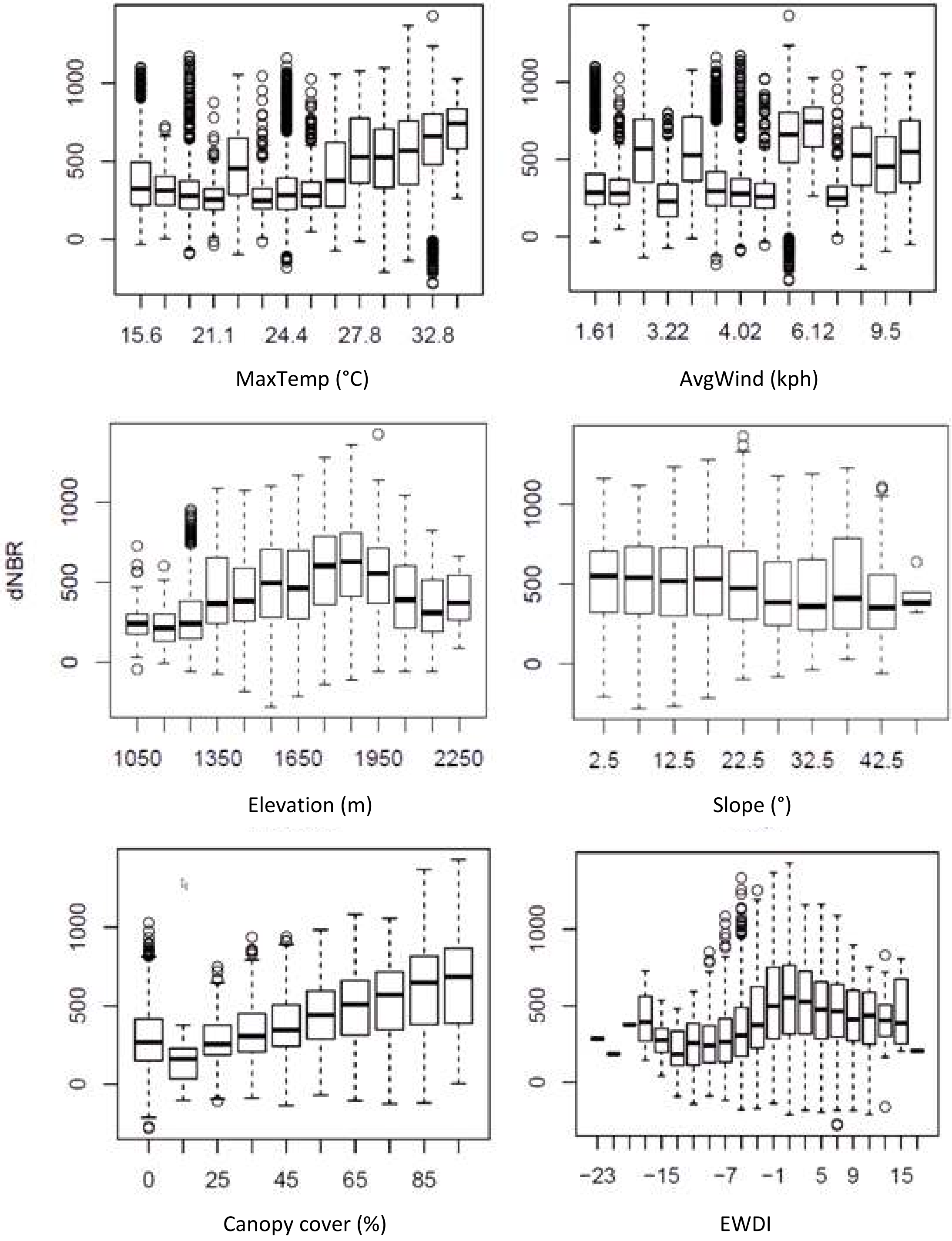

Figure 8: Box and whisker plots between dNBR and 6 predictor variables in the Tripod Fire. Individual box plots summarize dNBR values for binned values of each continuous predictor variable. Boxes represent the most common dNBR values between 25 and 75 percent with a 50 percent median line. Whiskers represent the minimum and maximum dNBR values, and outliers are indicated by circles.

6. Mountain Pine Beetles

A key question regarding MPB-affected forests is whether tree mortality following MPB outbreaks predisposes landscapes to high-severity crown fire, particularly during the red attack phase when dead needles dominate canopy fuels. The relationship between wildfire events and MPB outbreaks is still unclear in the published literature, and many uncertainties remain regarding fuel succession and fire hazard following MPB outbreaks (Kulakowski and Jarvis 2011, Hicke et al. *in press*, Jolly et al. *in press*,). One of the most important change agents on the pre-fire landscape was MPB and spruce beetle. However, MPB-affected forest vegetation, represented by the Mixed and Red classification of EWDI or more coarsely by high values of EWDI (Fig 7, 8), are only weakly related to dNBR, and relationships are not consistent between the two study areas (Table 2). In the Spur study area, the Mixed class has significantly higher dNBR values than the Green class, but the difference is only slight. In contrast, the Mixed class is actually negatively correlated to dNBR in the Tripod study area. In both study areas, the Regen class has significantly lower dNBR values than the Green classification, reflecting that areas that were wetter in August 2005 than August 2003 burned at lower severity than unchanged vegetation.

7. Validation of the fire severity layer

Field-based CBI values are highly correlated with dNBR and RdNBR values (R^2 = 0.71 for both indices)(Fig 9). Model residuals are evenly distributed, with no particular bias toward under- or over-predicting fire severity indices at extreme values. These results indicate that either index is suitable for representing fire severity for the Tripod Complex fires. In a regional assessment of fire severity in the North Cascades range, Cansler and McKenzie (*in review*) also found nearly identical relationships between dNBR and RdNBR and CBI values.

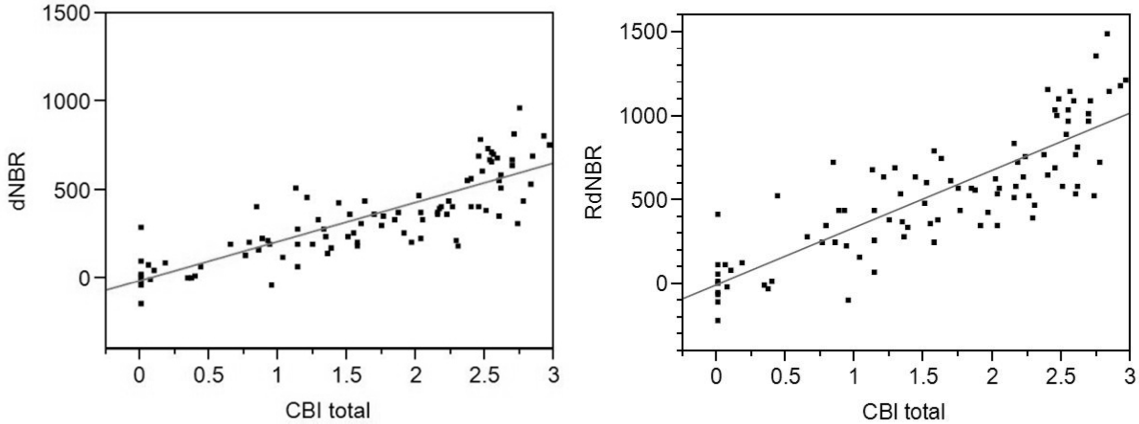

Figure 9: Simple linear models relating field-based composite burn index (CBI) to dNBR (dNBR ~ -8.409501 + 220.73129*CBI) and RdNBR (RdNBR ~ -0.144108 + 340.66029*CBI). Both models have the same coefficients of determination (R^2 = 0.71).

8. *Influence of treatment age and size on fire severity*

Models of fire severity by treatment category suggest that treatment age and size are only weakly significant predictors of fire severity (Table 4). When combined with other continuous predictor variables, including CanCov, Elev, Slope, MaxTemp, AvgWind, and EWDI (Table 1) they result in only slightly lower AIC model values. Treatment age is positively correlated with dNBR in the CCBB and ThinBB treatments but is not important in the CC, Thin and WF treatments. Using a standard fire severity classification of unburned (< 106), low (dNBR = 106-223) and moderate (dNBR = 223-476) after Cansler (2011), classification of fire severity would change from low to moderate severity at > 20 years in the CCBB units and > 30 years in the ThinBB treatment. Treatment size is a significant predictor of dNBR in all treatments but WF and is negatively correlated with dNBR. In the CC and ThinBB treatments, fire severity classification shifts from moderate to low with unit size > 200 ha, whereas CCBB change from low severity to unburned. In Thin treatments, classification of fire severity changes from moderate to low severity in unit size > 300 ha.

Across treatment categories, the weak influence of treatment age on fire severity predictions may be partly explained by the lack of treatments older than 30 years and the low primary productivity of vegetation in this semi-arid landscape. Fuel succession is slow in this study area, and prescribed burn treatments appear to have been effective across the range of treatment ages. In particular, clearcut and broadcast burn treatments were the most effective treatment in mitigating fire severity and appear to have been effective regardless of treatment area or time since treatment.

Table 4: Age and size models of dNBR by treatment type (CC = clearcut, CCBB = clearcut and broadcast burn, Thin = thin only, ThinBB = thin and broadcast burn, WF = wildfire). Slope and intercept values are included for simple models with only one predictor variable. Interaction terms are only included where they are significant and resulted in a substantial reduction in model AIC values. Best multiple regression models are presented for each treatment type with and without inclusion of treatment age and size.

Model	**Intercept**	**Slope**	**p**	**R^2**	**AIC**
CC					
dNBR ~ Age	245.99	0.8931	0.2340	0.0002	26433
dNBR ~ Size	300.39	-0.8151	< 0.0001	0.0148	26403
dNBR ~ Size + Age*Size + CanCov + Elev + Slope + MaxTemp	na	Na	na	0.1374	26151
dNBR ~ CC + Elev + Slope + MaxTemp	na	Na	na	0.1198	26180
CCBB					
dNBR ~ Size	206.64	-0.4911	0.5511	0.0001	26618
dNBR ~ Age	137.05	4.737	0.0021	0.0042	26609
dNBR ~ Age + CanCov + Elev + Slope + MaxTemp + AvgWind	na	Na	na	0.2429	26072
dNBR ~ CanCov + Elev + Slope + MaxTemp + AvgWind	na	Na	na	0.2425	26071
Thin					
dNBR ~ Size	322.28	-0.4936	<0.0001	0.0263	26482

Model	Intercept	Slope	p	R^2	AIC
dNBR ~ Age	320.79	-1.9746	0.0005	0.0055	26525
dNBR ~ Age + Size + Age*Size + CanCov + Elev + Slope + MaxTemp + AvgWind+ EWDI	na	Na	na	0.2224	26050
dNBR ~ CanCov + Elev + Slope + MaxTemp + AvgWind+ EWDI	na	Na	na	0.1964	26103
ThinBB					
dNBR ~ Size	190.35	0.2687	<0.0001	0.0252	25646
dNBR ~ Age	182.14	1.5237	<0.0001	0.0200	25656
dNBR ~ Age + Size + Age*Size + CanCov + Elev + MaxTemp + AvgWind	na	Na	na	0.1260	25456
dNBR ~ CanCov + Elev + MaxTemp + AvgWind	na	Na	na	0.1157	25454
WF					
dNBR ~ Size	322.58	-0.0126	<0.0001	0.0140	28158
dNBR ~ Age	269.85	1.4456	0.0013	0.0047	28177
dNBR ~ Age + Age*Size + CanCov + Elev + MaxTemp	na	Na	na	0.2194	27696
dNBR ~ CanCov + Elev + MaxTemp	na	Na	na	0.1708	27814

Management implications

This study corroborates previous research on fuel treatments and further demonstrates that prescribed burning is effective at mitigating wildfire severity in dry conifer forests (see Agee and Skinner 2005, Peterson et al. 2005, Reinhardt et al. 2008 for reviews). Even within extreme weather events, fuels and vegetation strongly influenced patterns of fire severity. Fuel treatments that included recent prescribed burning of surface fuels were particularly effective at mitigating fire severity. In contrast, units that are mechanically thinned from below and those with sanitation cuts in which small trees were cut and piled tended to burn at moderate to high severity. Treatment age and size are weak but significant predictors of burn severity. In general, burn severity increases slightly with treatment age and is reduced in larger treatment areas.

At low to mid-elevations with a historic low-severity fire regime, reintroducing frequent, low-severity fire through mechanical thinning and prescribed fire and/or prescribed burns without prior thinning are promising approaches to mitigating fire severity in future wildfire events. The management context for mitigating future wildfire severity is highly dependent on vegetation and fire regime. High elevation forests generally have a mixed to high-severity fire regime, characterized by less frequent and more severe fire events (Agee 1993). Because few species at high elevations are adapted to frequent fire, thinning projects and prescribed fire are generally not deemed appropriate or effective (Agee and Skinner 2005, Reinhardt et al. 2008). However, managing future wildfires to increase landscape heterogeneity and resilience to future extreme fire events are promising strategies at mid- to high-elevations (Moritz et al. 2010). Prescribed crown fires are also being implemented in the Canadian Rockies and elsewhere to create defensible fire breaks and increase landscape heterogeneity (Gray 2009).

Regional climate is also an important consideration for implementing fuel treatments. In the semi-arid climate of the Tripod Complex fires, many fuel treatments that were even two to three decades old still appeared to be effective at mitigating fire severity. In contrast, treatments may need to be repeated frequently (2-10 years) in more productive ecosystems, such as in the southeastern United States or other ecosystems with flammable shrub layers that could be released by thinning and prescribed burn treatments (Wade and Lunsford 1989, Marshall et al. 2008).

Relationship to other recent findings and ongoing work on this topic

Studies on drivers of fire severity

Several recent studies have published approaches for modeling drivers of wildland fire severity across forested landscapes in the western United States.

- Bigler et al. (2005) employed ordinal logistic regression to evaluate the effect of past fires, an old MPB outbreak, forest cover type, stand structure, and topography on a burn severity classification of dNBR from a 2002 Colorado wildfire (JFSP 03-2-2-01). They also found that elevation and vegetation type were important predictors of fire severity and that a past MPB outbreak resulted in a slight increase in fire severity.
- Finney et al. (2005) used conditional spatial autoregression analysis to evaluate the effectiveness of prescribed burning, time since treatment, unit size and burn frequency in mitigating fire severity in the 2002 Rodeo-Chedeski fires of Arizona. They found that prescribed burning and time since fire were important predictors of fire severity and resulted in significantly lower dNBR values.
- Collins et al. (2007) performed a regression tree analysis on dNBR in two recent fires in Yosemite National Park and examined landform, vegetation and weather as predictor variables (JFSP 01-1-16). Of the landform, weather, and vegetation variables they tested, they found that relative humidity, summarized by progression interval, and dominant vegetation type were the most important predictors of fire severity. Elevation, slope, temperature, wind speed, and time since last wildfire were also significant predictors.
- Kulakowski and Veblen (2007) used regression tree analysis to evaluate the effect of prior disturbances, including bark beetle outbreaks, blow downs, and salvage logging, on a burn severity classification of dNBR from a 2002 Colorado wildfire (JFSP 03-2-2-01). They found that previous blowdown areas burned at significantly higher severity than unaffected stands but that salvage logging and previous bark beetle outbreaks were not important predictors of fire severity.
- Wimberly et al. (2009) evaluated fuel treatment effectiveness on three recent California wildfires using ordinary least squared regression (OLS) and sequential autoregression (SAR) modeling of dNBR (JFSP 06-3-3-11). They found that prescribed burning and thinning followed by prescribed burning significantly reduced fire severity whereas thinning alone actually increased fire severity in two of the wildfire areas.
- Cansler and McKenzie (*in review*) evaluated climatic and landform drivers of fire severity in wildfires from 1984 to 2006. They found that climatic factors including spring snowpack and

summer temperature strongly influenced burn severity in past wildfires and that fires that burned in topographically complex landscapes had higher spatial complexity of burn severity.

Our analysis of the Tripod Complex fires found that climate, landform, and vegetation are important predictors of fire severity and in many ways corroborates these existing studies. Similar to the 2002 Rodeo-Chediski fires studied by Finney et al. (2005), the 2006 Tripod Complex fires burned under extreme fire weather and provided a test of whether treatments can remain effective even under weather-driven fire events. Although we studied an area with a recent MPB outbreak, we found that MPB affected stands were only weakly related to burn severity as did Bigler et al. (2005) and Kulakowski and Veblen (2007).

Research on the Tripod Complex fires

This study is an extension of a field-based study on fuel treatment effectiveness in the Tripod Complex (JFSP 07-1-2-13; Prichard et al. 2010, Prichard and Kennedy *in review*). Several additional studies have also been conducted where collaborations and data sharing were made possible due to our work in the Tripod Complex. These include:

- Lyons-Tinsley and Peterson (*in press*) conducted a study on fire severity in clearcut units.
- Another study (Restaino *in prep*) is being conducted on carbon fluxes in thin and prescribed burn units as compared to thin-only units using field data collected by Prichard et al. (2010).
- Two NASA summer internship projects were conducted in the Tripod Complex. Newcomer et al. (2008) evaluated remote sensing methods to detect fire severity and validated fire severity using CBI plots. Justice et al. (2009) used a sample of our field plots to evaluate carbon fluxes in treated and untreated units burned by the wildfires.
- Cansler (2011) used CBI plots from the Newcomer et al. 2008 and field data from Prichard et al. (2010) to validate fire severity in the Tripod Complex and within a pooled set of recent fires across the North Cascades range.

Studies on fuel treatment effectiveness in the western United States

Results from our field-based study (Prichard et al. 2010) and current landscape analysis of fire severity are markedly similar and in close agreement with published studies on fuel treatment effectiveness in the western United States. Combined, these studies demonstrate the effectiveness of prescribed burning in mitigating wildfire severity. The following summarizes similar studies on this topic:

- Pollett and Omi (2002) evaluated fuel treatment effectiveness in four ponderosa pine sites throughout the western United States and found that all treatments (whole-tree harvesting, thin and prescribed burn, and prescribed fire only) had significantly lower wildfire severity than untreated stands.
- In a study of fire severity following the 2003 Cone Fire in northern California, Ritchie et al. (2007) report highest tree survivorship in units that were thinned and prescribed burned compared to thin-only and untreated units.

- Strom and Fulé (2007) studied thinned units where slash had been piled and burned in the Rodeo-Chediski fire and found significant reductions in fire severity compared to untreated stands.
- Safford et al (2009) report significant differences in tree mortality in thinned units where slash had been piled and burned relative to untreated areas in the Angora fire, CA.
- The effectiveness of fuel reduction programs, prescribed burning in particular, is also supported by fire behavior and effects modeling (Stephens and Moghaddas 2005, Moghaddas et al. 2010, Johnson et al. 2011). The national Fire and Fire Surrogates study also demonstrated that prescribed burn treatments were more effective than mechanical treatments at reducing surface fuels (Schwilk et al. 2009).

Future work needed

Analysis of bottom-up controls of fire behavior during extreme fire weather events

Given climatic change predictions, much emphasis has been placed on top-down climatic controls of fire (Gillett et al. 2004, Gedalof et al. 2005, Westerling 2006, Heyerdahl et al. 2008, Morgan et al. 2008, Littell et al. 2009). The relative influence of bottom-up controls (e.g., landform, vegetation and fuels) on fire severity and spread, even in weather-driven events, has received relatively little attention. For example, we know that regional fire years are responsible for the majority of wildfire area burned, and the increase in wildfire severity and area burned over the past 30 years has been linked to earlier spring snowmelt and warmer summers. Under climatic change scenarios, wildfires should increase in severity and extent (Miller et al. 2008). However, at some point, recent wildfires may limit the severity and spread of future wildfires due to their influence on the amount and continuity of available fuels across landscapes (Moritz et al. 2010).

Key questions that could guide future research include:

- What are the thresholds at which fuels limit fire spread and behavior, particularly under weather-driven fire events?
- Do past wildfires influence wildfire spread and severity?
- Can fuel treatments be designed to modify fire behavior and spread? FARSITE modeling (Finney 2007) indicates that treatment configuration can slow fire spread, but few opportunities exist to quantitatively evaluate effectiveness of treatment configurations. Real-time observations of wildfire behavior in treated units are also rare.
- How can scientists contribute to better management of wildfires for resource benefit?

Influence of past disturbances on fire severity

Few studies have evaluated the influence of past wildfires on fire severity (but see Collins et al. 2007, Keane et al. 2008, Wimberly et al. 2009 and Thompson and Spies 2009). Given the potential for recent wildfires to influence the spread and severity of future wildfires, more work is needed in this area, particularly in assisting managers with guidance on where and when to allow wildfires to burn. The influence of recent wildfires on fire severity was somewhat mixed in this study. Recent high-severity wildfires clearly influenced fire spread with little reburn of old fire scars. However, in the Tripod study area, older wildfires tended to burn at higher severity than untreated forests.

The impact of an ongoing MPB and spruce beetle outbreak on wildfire severity was inconclusive in this study. Theoretically, forests with a high percentage of red-needled crowns should have a higher probability of crown fire initiation and spread (Hicke et al. *in press*). However, classification of red attack pixels was only weakly correlated to fire severity and had opposing effects in our two study areas. Field-based studies that include pre- and post-fire fuel characterization may be necessary to address how recent bark beetle activity may influence fire behavior and effects. Use of prescribed crown fire experiments would be particularly instructive to characterize pre-burn surface and canopy fuels and evaluate fire behavior across stages of MPB outbreak.

Treatment duration

Our analysis revealed only weak relationships between treatment age and fire severity, likely because geospatial records only cover the past 30 years of treatments, and fuel succession is slow in these forested ecosystems. More work is clearly needed on predicting fuel succession in forested ecosystems and how long certain fuel treatments will remain effective at mitigating fire severity.

Quantitative analysis of fuel treatments as defensible space and impacts of firefighting

After hearing from fire behavior analysts and local managers that some burnout (or backfiring) operations in the Tripod Complex contributed to extreme fire behavior and spread, we were interested in spatially reconstructing firefighting activities and evaluating fire severity in burnout areas. We compiled daily Incident Action Plans and firefighting notes from type I and II teams, but there were too many uncertainties to construct an actual geospatial layer that contained bulldozer lines and burnout locations. Some observations from local managers and fire behavior analysts are that 1) some burnouts were done too rashly and resulted in nearly 100% mortality even in low-elevation ponderosa pine forests, 2) one burnout that was conducted late in the fire season may have resulted in the wildfire jumping containment lines and taking a large run into a wilderness area, and 3) bulldozer lines that were used extensively in the southern and eastern flanks of the Tripod Complex were ineffective barriers to fire spread.

Given the potential for fuel treatments to act as defensible space, an interesting study would be to embed research scientists in Type I and II teams to spatially record firefighting activities so that retrospective burn severity analysis could be conducted. Similarly, spatially and temporally accurate records of bulldozer lines and burnout areas would assist in retrospective analysis of 1) which firefighting activities were effective at limiting fire severity and spread, and 2) potential impacts of firefighting on soils and vegetation relative to undefended areas.

Deliverables

We completed all of the deliverables proposed for this study. A scientific manuscript is under peer review for submission to *Ecological Applications*. We will submit the *Fire Management Today* manuscript after the scientific manuscript has been published. Other deliverables completed under this project but not included in the JFSP proposal include an additional scientific manuscript, participation in scientific conferences and an invited presentation to an all-staff meeting of the Okanogan-Wenatchee National Forest.

Table 6: Proposed and additional deliverables.

Proposed	**Delivered**	**Completion Date**
JFSP progress report 1	Progress report to JFSP for FY 2009	September 2009
JFSP progress report 2	Progress report to JFSP for FY 2010	September 2010
JFSP progress report 3	Progress report to JFSP for FY 2011	September 2011
Local presentation to managers	Invited presentation to Okanogan-Wenatchee National Forests leadership team, Mazama, Washington	September 14, 2010
Manuscript	Prichard, S.J., Freed, T., and Peterson, D.L. *In review*. Fuel treatments and landform modify fire severity in an extreme fire event. Ecological Applications.	January 2012
Article	Article for *Fire Management Today* to be submitted after publication of the scientific manuscript	Draft completed January 2012
Webpage	A summary of Tripod research and available downloads (published papers, final reports, and data layers) has been posted at: http://www.fs.fed.us/pnw/fera/research/treatment/tripod	January 2012
JFSP Final Report	Final report to JFSP	Submitted January 31, 2012
Additional deliverables (not in original proposal)		
Poster presentation	Poster presentation: "Evaluating fuel treatment effectiveness in the 2006 Tripod Complex fires, Washington State, USA," 6th International Conference on Forest Fire Research in Coimbra, Portugal. Awarded first prize in poster competition.	November 3, 2010
Presentation to managers	Invited presentation to the Okanogan-Wenatchee National Forest all-staff meeting, Cashmere, Washington	May 12, 2011
Oral presentation	Oral presentation: "Landscape analysis of fuel treatments and wildfire severity in north-central Washington State," Interior West Fire Ecology Conference, Nov 14-16, 2011. Snowbird, Utah.	November 16, 2011
Scientific manuscript	Prichard, S.J. and Kennedy, M.C. In review. Fuel treatments reduce the severity of wildfire effects in dry mixed conifer forest, Washington, USA. International Journal of Wildland Fire.	Accepted with minor revisions (January 2011)

References

Agee, J.K. 1993. Fire Ecology of Pacific Northwest Forests. Island Press, Washington, D.C.

Agee, J.K. and Skinner, C.N. 2005. Basic principles of forest fuel reduction treatments. Forest Ecology and Management 211:83-96.

Beers, T.W., Dress, P.E., and Wensel, L.C. 1966. Aspect transformation in site productivity research. Journal of Forestry 64: 691.

Bessie, W.C., and Johnson, E.A. 1995. The relative importance of fuels and weather on fire behavior in subalpine forests. Ecology 76: 747-62.

Bigler, C., Kulakowski, D. and Veblen, T.T. 2005. Multiple disturbance interactions and drought influence on fire severity in Rocky Mountain subalpine forests. Ecology 86:3018-3029.

Cansler, C.A. 2011. Drivers of burn severity in the northern Cascade Range, Washington, USA. M.S. Thesis, University of Washington, Seattle, WA.

Cansler, C.A. and McKenzie, D. *In review*. How robust are burn severity indices when applied in a new region? Evaluation of alternative field-based and remote sensing methods. Remote Sensing.

Collins, B.M., Kelly, M. van Wagtendon, J.W., and Stephens, S.L. 2007. Spatial patterns of large natural fires in Sierra Nevada wilderness areas. Landscape Ecology 22:545-557.

Eidenshink, J., Schwind, B. Brewer, B., Zhu, Z., Quayle, B. and Howard, S. 2007. A Project for Monitoring Trends in Burn Severity. Fire Ecology 3:3-21

Finney, M.A., McHugh, C.W., and Grenfell, I.C. 2005. Stand- and landscape-level effects of prescribed burning on two Arizona wildfires. Canadian Journal of Forest Research 35: 1714-1722.

Finney, M.A. 2007. A computational method for optimizing fuel treatment locations. International Journal of Wildland Fire 16: 702–711.

Gedalof, Z.M., Peterson, D.L. and Mantua, N.J. 2005. Atmospheric, climatic and ecological controls on extreme wildfire years in the northwestern United States. Ecological Applications 15: 154-174.

Gillett, N.P., Weaver, A.J., Zwiers, F.W., and Flannigan, M.D. 2004. Detecting the effect of climate change on Canadian forest fires. Geophysical Research Letters 31: L18211.

Gray, R.W. 2009. Influence of Fuel Treatment, Burn Severity, and Site Characteristics on Vascular Plant Species Richness on the Mitchell Ridge Prescribed Burn, Kootenay National Park, BC. Proceedings. 4th International Fire Ecology and Management Congress: Fire as a Global Process. Savannah, GA.

Heyerdahl, E.K., Morgan, P., and Riser, J.P., 2008. Climate drivers of regionally synchronous fires in the inland Northwest (1651-1900). International Journal of Wildland Fire 17: 40-49.

Hicke, J.A., Johnson, M.C., Hayes, J.L., and Preisler, H.K. *In press*. Effects of bark beetle-caused tree mortality on wildfire. Forest Ecology and Management.

Johnson, E.A. and Miyanshi, K. 2001. Forest Fires: Behavior and Ecological Effects. Academic Press, San Diego, CA.

Johnson, M.C., Kennedy, M.C, and Peterson, D.L. 2011. Simulating fuel treatment effects in dry forests of the western United States: testing the principles of a fire-safe forest. Canadian Journal of Forest Research 41: 1018-1030.

Jolly, W.M., Parsons, R., Varner, J.M., Butler, B.W., Ryan, K.C., and Gucker, C.L. *In press.* Do mountain pine beetle outbreaks change the probability of active crown fire in lodgepole pine forests? Comment. Ecology.

Justice, E., Cheung, B., Danse, W., Myrick, K., Willis, M., Prichard, S., Skiles, J.W. 2009. Effect of fuel treatments on carbon flux during a wildfire using satellite imagery: Okanogan-Wenatchee National Forest. Proceedings ASPRS 2009 Annual Conference.

Kazar, B.M., Shekhar, S., Lilja, D.J., Vatsavai, R.R., and Pace, R.K. 2004. Comparing exact and approximate spatial auto-regression model solutions for spatial data analysis. Proceedings, Third International Conference on Geographic Information Science, Adelphi, MD.

Keane, R.E., Agee, J.K., Fulé, P., Keeley, J.E., Key, C., Kitchen, S.G., Miller, R., and Schulte, L.A. 2008. Ecological effects of large fires US landscapes: benefit or catastrophe? International Journal of Wildland Fire 17: 696-712.

Key, C. H. 2006. Ecological and sampling constraints on defining landscape fire severity. Fire Ecology 2:34-59.

Kulakowski, D. and Jarvis, D. 2011. The influence of mountain pine beetle outbreaks and drought on severe wildfires in northwestern Colorado and southern Wyoming: a look at the past century. Forest Ecology and Management 262: 1686-1696.

Kulakowski, D. and Veblin, T.T. 2007. Effect of prior disturbances on the extent and severity of wildfire in Colorado subalpine forests. Ecology 88: 759-769.

LANDFIRE. U.S. Department of Interior, Geological Survey. [Online]. Available: http://landfire.cr.usgs.gov/viewer/ [2011, November 13].

Littell, J.S. and Gwozdz, R.B. 2011. Climatic water balance and regional fire years in the Pacific Northwest, USA: linking regional climate and fire at landscape scales. In D. McKenzie et al. (eds.) The Landscape Ecology of Fire, Springer, Dordrecht, The Netherlands.

Littell, J.S., McKenzie, D., Peterson, D.L., and Westerling, A.L. 2009. Climate and wildfire area burned in western U.S. ecoprovinces, 1916-2003. Ecological Applications 19: 1003-1021.

Lyons-Tinsley, C. and Peterson, D.L. *In press*. Surface fuel treatments in young, regenerating stands affect wildfire severity in a mixed conifer forest, eastside Cascade Range, Washington, USA. Forest Ecology and Management.

Marshall, D.J., Wimberly, M., Bettinger, P. Stanturf, J. 2008. Synthesis of knowledge of hazardous fuels management in loblolly pine forests. GTR-SRS-110, U.S. Forest Service, Southern Research Station, Asheville, NC.

Miller, J.D., Knapp, E.E., Key, C.H., Skinner, C.N., Isbell, C.J., Creasy, R.M., and Sherlock, J.W. 2009. Calibration and validation of the relative differenced Normalized Burn Ratio (RdNBR) to three measures of fire severity in the Sierra Nevada and Klamath Mountains, California, USA. Remote Sensing of Environment 113: 645-656.

Miller, J.D., Safford, H.D., Crimmins, M., and Thode, A.E. 2008. Quantitative evidence for increasing forest fire severity in the Sierra Nevada and southern Cascade Mountains, California and Nevada, USA. Ecosystems 12: 16-32.

Miller, J. D. and Thode, A.E. 2007. Quantifying burn severity in a heterogeneous landscape with a relative version of the delta Normalized Burn Ratio (dNBR). Remote Sensing of Environment 109: 66−80.

Miller, J.D. and Yool, S.R. 2002. Mapping forest post-fire canopy consumption in several overstory types using multi-temporal Landsat TM and ETM data. Remote Sensing of Environment 82: 481−496.

Moghaddas, J.J., Collins, B.M., Menning, K., Moghaddas, E.E.Y. and Stephens, S.L. 2010. Fuel treatment effects on modeled landscape level fire behavior in the northern Sierra Nevada. Canadian Journal of Forest Research 40: 1751-1765.

Morgan, P. Heyerdahl, E.K., and Gibson, C.E. 2008. Multi-season climate synchronized forest fires throughout the 20th century, northern Rockies, USA. Ecology 89: 717-728.

Moritz, M.A., Hessburg, P.F., and Povak, N.A. 2010. Native fire regimes and landscape resilience. In D. McKenzie et al. (eds.) The Landscape Ecology of Fire, Springer, Dordrecht, The Netherlands.

Newcomer, M., Delgado, D., Gantenbein, C., Wang, T., Schiffman, B., Prichard, S., Schmidt, C., and Skiles, J.W. 2008. Burn severity assessment in the Okanogan-Wenatchee forest using NASA satellite missions. Proceedings ASPRS 2008 Annual Conference.

Peterson, D.L., Johnson, M.C., Agee, J.K., Jain, T.B., McKenzie, D. and Reinhardt, E.R. 2005. Forest structure and fire hazard in dry forests of the western United States. PNW-GTR-628. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station.

Peterson, G.D. 2002. Contagious disturbance, ecological memory, and the emergence of landscape pattern. Ecosystems 5: 329–338.

Pollett, J. and Omi, P.N. 2002. Effect of thinning and prescribed burning on crown fire severity in ponderosa pine forests. International Journal of Wildland Fire 11: 1-10.

Prichard, S.J., Peterson, D.L., and Jacobson, K., 2010. Fuel treatments reduce the severity of wildfire effects in dry mixed conifer forest, Washington, USA. Canadian Journal of Forest Research 40: 1615–1626.

Prichard, S.J. and Kennedy, M.C. *In review*. Fuel treatment effects on postfire tree mortality and beetle attack in dry mixed conifer forests, Washington State, USA. International Journal of Wildland Fire.

R Development Core Team. 2011. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org.

Reinhardt, E.D., Keane, R.E., Calkin, D.E., and Cohen, J.D. 2008. Objectives and considerations for wildland fuel treatment in forested ecosystems of the interior western United States. Forest Ecology and Management 256: 1997-2006.

Restaino, J. *In prep*. Wildfire and fuel treatment effects on carbon storage, eastside Cascade Range, Washington, USA. M.S. Thesis, University of Washington.

Ritchie, M.W., Skinner, C.N., and Hamilton, T.A. 2007. Probability of tree survival after wildfire in an interior pine forest of northern California: effects of thinning and prescribed fire. Forest Ecology and Management 247:200-208.

Safford, H.D., Schmidt, D.A., and Carlson, C.H. 2009. Effects of fuel treatments on fire severity in an area of wildland–urban interface, Angora Fire, Lake Tahoe Basin, California. Forest Ecology and Management 258: 773-787.

Schwilk, D.W., Keeley, J.E., Knapp, E.E., McIver, J., Bailey, J.D., Fettig, C.J., Fiedler, C.E., Harrod, R.J., Moghaddas, J.J., Outcalt, K.W., Skinner, C.N., Stephens, S.L., Waldrop, T.A., Yaussy, D.A. and Youngblood, A. 2009. The national Fire and Fire Surrogate study: effects of fuel reduction methods on forest vegetation structure and fuels. Ecological Applications 19: 285-304.

Soverel, N.O., Perrakis, D.D.B and Coops, N.C. 2010. Estimating burn severity from Landsat dNBR and RdNBR indices across western Canada. Remote Sensing of Environment 114: 1896-1909.

Stephens, S.L. and Moghaddas, J.J. 2005. Experimental fuel treatment impacts on forest structure, potential fire behavior, and predicted tree mortality in a California mixed conifer forest. Forest Ecology and Management 215:21-36.

Strom, B.A and Fulé, P.Z. 2007. Pre-wildfire treatments affect long-term ponderosa pine forest dynamics. International Journal of Wildland Fire, 16: 128-138.

Thompson J. R. and Spies, T. A. 2009. Vegetation and weather explain variation in crown damage in a large mixed-severity wildfire. Forest Ecology and Management 258: 1684-1694.

Turner, M.G. and Romme, W.H. 1994. Landscape dynamics in crown fire ecosystems. Landscape Ecology 9: 59-77.

Wade, D.D. and Lunsford, J.D. 1989. A guide for prescribed fire in southern forests.US Forest Service, Southern Region Technical Publication R8-TP-11, Atlanta, GA

Westerling, A.L., Hidalgo, H.G., Cayan, D.R., and Swetnam, T.W. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. Science 313: 940–943.

Wimberly, M.C., Cochrane, M.A., Baer, A.D., and Pabst, K. 2009. Assessing fuel treatment effectiveness using satellite imagery and spatial statistics. Ecological Applications 19: 1377-1384.

Wulder, M. A., Dymond, C. C., White, J. C., Leckie, D. G., and Carroll, A. L. 2006. Surveying mountain pine beetle damage of forests: A review of remote sensing opportunities. Forest Ecology and Management 221: 27−41.

Zhu, Z., Key, C., Ohlen, D. and Benson, N. 2006. Evaluating sensitivities of burn-severity mapping algorithms for different ecosystems and fire histories in the United States. Final Report to the Joint Fire Science Program, Project JFSP 01-1-4-12, October 12, 2006. 35 pp.