BURN SEVERITY AND TERRAIN: A SPATIAL ANALYSIS OF FOREST FIRE BURN SEVERITY TRENDS IN THE WESTERN UNITED STATES

by
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A thesis submitted
In partial fulfillment of the requirements
For the degree of
Master of Science
(Natural Resources and Environment)
in the University of Michigan
August 2008

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Abstract

Differenced normalized burn ratio (dNBR) is a remote sensing technique measuring forest fire burn severity – the post-fire effects on local forest ecology. Understanding how dNBR varies across landscapes as fuel, local weather conditions, and terrain changes provides useful insight into the possible application of dNBR as a data source for fuel consumption and emission modeling. This study evaluated dNBR terrain trends in nineteen forest fires in the Western conterminous United States that burned from 2000 to 2003. Terrain variables tested for possible correlation with dNBR included elevation, slope, aspect, and annual incident solar radiation. Linear results proved significant ($p < 0.05$) for elevation, slope, and annual incident solar radiation but with low coefficients of determination. Categorical analyses of variance found significant mean differences in all severity classes for each terrain variable. Results demonstrate that terrain controls on dNBR in these fires emerge over large scales as terrain alters local vegetation and fire behavior trends.

Acknowledgements

I would like to thank my thesis committee for their support through the research and writing process. Without their insight, experience, and keen guidance this thesis would not have been possible. Robert Grese provided sound advice on research organization, fire ecology, and project scope. The statistical and spatial analysis background of Dan Brown proved invaluable in tightening up the research document as well as improving the results presentation. Nancy French has many years of experience working in the fire ecology field. Her advice in building the experimental design and interpreting the results provided a solid theoretical background.

In addition to my committee, I would also like to thank my friends and colleagues at the Michigan Tech Research Institute for providing advice and, on occasion, use of their facilities.

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Chapter 1. Introduction

Fire is an important mechanism in many terrestrial ecosystems. The fire process releases carbon stored in living and dead plant biomass and allows plants access to often limited nutrients. In the past, the role of fire in forested ecosystems was grossly misunderstood, leading to strict fire suppression strategies by many forest management agencies. With fire suppression, dead plant biomass, in the form of forest litter and woody debris, accumulates in unnatural levels increasing fire intensity when burns occur (Keane, Burgan and Wagtendonk). As the understanding of forest ecosystem successional dynamics improved and the dangers associated with suppression were better known, the need to manage forest ecosystems with more natural fire regimes was recognized. Managing these systems to (1) facilitate healthy forests and (2) protect the population and economic assets at risk to fire became priorities for many forest management agencies (Chuvieco, Allgower and Salas).

Fire is also an important component of the global carbon cycle providing both sources, directly through combustion, and sinks, indirectly through succession following disturbance (Michalek et al.). The recognition of global climate change as a primary social challenge has placed renewed interest on the fire cycle and its dynamics. While interest remains in the direct ecological effects on ecosystem processes, broad-scale studies of fire pattern have taken a leading role in documenting and predicting the release and sequestration of carbon in forest ecosystems (Conard et al.; Kasischke et al.). Furthermore, interest in the effects of global warming on the fire regime have lead to the tentative conclusion that rising global temperatures will manifest in decreased fire return intervals for many forest ecosystems while increasing fire severity and intensity (Bergeron; Wotton and Flannigan).

The need for large-scale fire assessments has lead to the integration of multiple research fields and analysis methods that have become readily available in the last two decades. Spatial information systems permit the storage, analysis, and presentation of attributed data with high geographical accuracy. Remote sensing, the imaging of earth's surface with airborne and spaceborne optical systems, has also provided a highly useful method to retrieve information on terrestrial ecosystems. Ground assessment, while providing an accurate portrayal of surface conditions, is often incapable of synoptic landscape assessment due to limiting factors such as budget and realistic timeframes. Remote sensing, coupled with other spatial information systems (i.e. geographical information systems [GIS]) is an ideal mechanism to retrieve this synoptic information (White et al.) and make it available for large-scale planning and management.

This thesis reports on an analysis of the Differenced Normalized Burn Ratio (dNBR) as a remote method to model and predict fire severity as a function of terrain (elevation, slope, aspect, and annual incident solar radiation) variables. The dNBR is a spectral index derived from satellite imagery responsive to fire effects in discrete spectral bandwidths providing a rapid, inexpensive method to measure fire severity over large areas. Research combining dNBR and ground-based assessments of fire severity has proven a correlation between the metric and measurable ecological effects (Key and Benson). Recently, an initiative by the U.S. Geological Survey (USGS) has created and compiled burn severity maps of major forest fires in the conterminous United States (USGS "Monitoring Trends in Burn Severity (Mtbs)"). With a large quantity of spatial fire severity data readily available, it is possible to test hypotheses across diverse ecological, topographical, and climatic gradients. Also useful is testing the utility of dNBR in measuring more than "ecological effects" by informing emission / consumption models.

The hypothesis evaluated here can be stated as follows: Surrogate measures of fuel moisture, density, and structure are correlated with burn severity as these characteristics influence fire intensity, behavior, and fuel consumption. The surrogate measure used to test the information potential of dNBR in this regard is terrain. Relationships between terrain and dNBR not visible in smaller datasets may manifest when larger datasets comprised of multiple fires with varying physical, ecological, and burning properties are combined. The broader research goal is to inform carbon emission models from forest fires. Fuel moisture, density, and structure are important input variables when predicting emissions and consumption from forest fires due to their direct relationship with burn temperature (Bradshaw et al.). Identifying possible links between dNBR and fuel properties is an important first step in the potential application of dNBR to emission modeling.

Terrain Variable	Description
Elevation	Height above reference datum.
Slope	Angular position relative to horizontal reference.
Aspect	Orientation relative to northern azimuth.
Annual Incident Solar Radiation	Average annual solar radiation.

Table 1. List of Terrain Variables Tested for dNBR Relationships.

Four terrain variables (listed in Table 1) describing landscape position, orientation, and photosynthetic potential are tested for linear and categorical statistical relationships with dNBR. Using a combination of GIS and statistical software, each variable is calculated, spatially registered to a dNBR map, and then tested using linear regressions and one-way analyses of variance (ANOVA).

The following is a description of the organization of this research document. Chapter 2 is a literature review providing background information on (1) fire science describing the terminology used in this introduction (i.e. severity, intensity, fuel moisture, fuel bed, etc.), (2) a description of the independent variable dNBR covering its calculation and research relevant to this study, (3) a description of the dependent variables and their relationships to fuel moisture, density, and structure, and (4) rationale for the applied statistical method. Chapter 3 will describe the methods used – data preparation and the statistical approach. Chapter 4 presents the results. Chapter 5 is a discussion of the results with special attention paid to limitations and improvements on the methods. Appendices contain example datasets in tabular format as well as visual representation of the data.

Chapter 2. Background on Fire Behavior

Fire is defined by Widener (:81) as: "rapid oxidation, usually with the evolution of heat and light; heat, fuel, and oxygen and the interaction of the three." This combustion reaction continues until a chemically stable state is reached leaving the byproducts of carbon dioxide and water. The primary fire processes include ignition, pyrolysis, and emission. Ignition occurs when a material absorbs a sufficient quantity of heat and energy to ignite and burn. In terrestrial ecosystems, this is often lightning, an artificial flame source, or, in extreme cases, a specific condition of the microclimate permitting sufficient dryness and heat to reach an ignition point. Pyrolisis is the process of burning wherein fuel is consumed and the exothermic chemical reaction that drives flaming occurs. Emission is the release of the chemical components comprising a fuel source and typically consists of 67% carbon dioxide, 25% water, 6% carbon monoxide, 1% suspended particulates, 0.9% hydrocarbons and organics, and 0.1% nitrogen oxides (emission percentages being approximate) (Omi).

The "fire triangle" consisting of fuel, oxygen, and heat is commonly used to describe the necessary ingredients for fire to occur (Omi 2005). Absence of any one of the ingredients results in extinction, the cessation of burning. Fire is a dynamic process. The "fire triangle" is generalization of the complex physical, chemical, and physiological structure of the fire environment (Pyne, Andrews and Laven). This research is concerned with emissions, one of the final byproducts of the consumptive fire process. Fuel moisture and intensity directly affect emission quantity and the ability to identify important environmental characteristics acting to influence these relationships comprises this, and many studies focused on quantifying forest fire emissions (Andreae; Dixon and Krankina; Kasischke et al.).

Estimating emissions from forest fires is enigmatic, confounded by numerous physiographic, climatic, and fire behavior properties. Substantial research, best described as fire ecology, focuses on describing variables that affect the intensity, duration, and emissions of forest fires (Agee <u>Fire Ecology of Pacific Northwest Forests</u>). Conditioning each of these fire properties is the fuel bed, the physical properties that define the characteristics and quantity of fuel available for a fire. Three primary fuel layers compose a typical forest fuel bed: (1) duff (accumulated forest litter of needles, leaves, and fine woody material), (2) downed woody fuels, and (3) live fuels (grasses, forbs, and tree biomass). While each component layer exhibits different burn behaviors, the moisture content in each layer universally influences fire intensity and consumption levels while the fuel quantity, fuel chemical composition, and burn efficiency affects emissions (Whelan).

The study area for this research includes fires occurring in Western and Pacific forest biomes typified by high elevations and low annual precipitation (Agee, Finney and Gouvenain; Cwynar; Heinselman). Forests types are predominantly lodgepole pine, pinyon-juniper, and ponderosa pine with scatterings of deciduous oak varieties. Under natural conditions, fire return intervals in the study area vary along a gradient from five years (ponderosa pine) to 40 years (lodgepole pine). Intervals are approximations based primarily on dendrochronological averaging with variability within a forest biome in some occasions matching the variability between biomes (Heyerdahl, Brubaker and Agee). Fire suppression in forest ecosystems such as ponderosa pine and pinyon-juniper characterized by more frequent, less intense burns has caused an increase in ground fuels and a more stratified canopy complex. Fires in these fire-suppressed ecosystems have, in many cases, matched the intensity of higher severity / intensity regimes in recent years due to the modification of fuels from suppression (V. H. Dale et al.; Franklin and Agee).

Fuel variability within a fire is, in many cases, equivalent to fuel variability across a landscape (Brown and Bevins). Hence, fuel characteristics, such as fuel moisture, are difficult to characterize as the physical and physiological spatial structure of the fuels changes rapidly. Primary controls of fuel moisture content fall into two categories: localized weather and fuel loading. Weather factors include the amount of precipitation, wind, cloud cover, temperature, and humidity. Each weather variable either provides an input of moisture (i.e. precipitation), a moisture egress (i.e. wind), or a moisture flux dependent upon the variable condition itself (i.e. low humidity / high humidity). Fuel bed moisture is separated between live and dead fuel moisture. Dead fuel moisture fluxes to a much higher degree than its live counterpart (Pyne, Andrews and Laven). During flaming, it is often the structure and composition of the dead fuel moisture driving the horizontal and vertical movement of the fire. Dead fuel moisture is organized into time-lag fuel moisture categories. These categories are reported in Table 2.

Diameter (inches)	Timelag (hours)
0 - 0.25	1
0.26 - 1	10
1.1 - 3	100
3.1 - 9	1000
9.1 - 20	10000
20.1+	10000+

Table 2. Fuel Timelag Definitions. Timelag fuel classes are calculated by measuring the time required for a fuel size to reach moisture equilibrium with ambient humidity conditions.

Fuel loading is a function of natural and anthropogenic processes. Forest litter and downed woody debris accumulate according to ecosystem type, maturity, and disturbance processes. For example, windthrow events cause the mass toppling of mature trees thereby greatly increasing the quantity of dead organic matter. Furthermore, the living fuel structure is changed as small live fuels accumulating during early succession create a different fire environment (Ulanova). In addition, local forest ecology directly influences the deposition of litter and debris – an ecological record often called “stand history” (Olson). In dryer climates, fire acts as a successional mechanism to remove debris and the forest overstory to trigger the development of new biomass. Wetter climates rely more heavily on the natural decomposition of litter by soil organisms than traumatic fire events (Harmon et al.). Anthropogenic alteration of the fire regime, namely suppression, greatly affects the natural processes of deposition, decomposition, and removal (Agee "The

Landscape Ecology of Western Forest Fire Regimes"). In Western states such as Oregon, Washington, and California, fuel availability has been affected by the western pine beetle (*Dendroctonus brevicomis*) resulting in stand die-offs. These infestations, often coupled with drought-like conditions, increases forest fire susceptibility (DeMars and Roettgering).

Measuring Fire Effects

It is evident with the intersection of natural and anthropogenic stand history that geographic controls on fire regime and specific burn properties are strong (Heinselman; Payette et al.). Modeling the internal variability of fuel beds is increasingly difficult as exigencies are incorporated. Remote sensing of post-fire effects offers a potential solution to documenting this variability through empirical data generation independent of assumption; data are gathered in an identical manner affected only by the optical uncertainties of an imaging system. Before discussing the specifics of the remote sensing products, a description of terminology used by fire scientists to describe fire effects is required.

Most importantly, a distinction must be drawn between two common descriptive fire properties must be drawn: intensity and severity. Fire intensity is a quantitative measure of energy, in the form of heat, released during burning (Widener). In addition, fire intensity also encompasses flame length, rate of spread, and amount and location of torching (Jain). Fuel availability, three-dimensional structure, and moisture content affect fire intensity, these measures varying across a landscape as local ecology changes (Arno). Confusion surrounds the use of severity to describe a fire's effects. Severity's current definition splits it into two categories defining first-order effects (fire severity) and second-order effects (burn severity) (Jain). Fire severity describes the immediate effect a fire has on the environment: killing of plants, soil heating, smoke production, and forest floor consumption. Burn severity describes the erosion of soils, introduction of new plant species, and regrowth of surviving plant species.

Burn severity is a measure of fire's effects on an ecosystem, incorporating tree mortality, consumption, burn scarring, and successional impact (French et al.; Key and Benson). It is often thought of as a magnitude, the degree of environmental change resulting from a burn. Another useful method to characterize severity is considering the change in aboveground biomass after a fire – a high reduction in biomass occurs with a severe fire. High severity burn areas often have the highest impact on forest stands (immediate and successional) while other cover types (i.e. grass, shrub) do not necessarily exhibit this same response (Jakubauskas, Lulla and Mausel).

Discussion and Definition of Analysis Variables

Burn severity is the fire property measured by dNBR. Informing emissions models from dNBR maps requires defining a link between the dNBR measure and the emission process. The terrain metrics described below are explained in the context of their potential influence on emission / consumption. In most cases, the variable and its effects on fuel structure, fuel deposition, fuel moisture, and fire behavior are noted. First, the calculation of dNBR will be discussed. This will be followed by descriptions of the independent variables and their relevance to this analysis. Lastly, studies utilizing a similar approach to this severity assessment are described.

Differenced Normalized Burn Ratio

The dNBR is a remote sensing differencing method utilizing the near-infrared (0.76-0.90 µm) and short-wave infrared (2.08-2.35 µm) spectral bands on Landsat 5 or 7 (Bands 4 and 7 respectively). Figure 1 contains an exampled dNBR map following thematic classification. Carl H. Key and Nathan C. Benson, at the Forest Service's Rocky Mountain Research Station, developed this assessment technique in pursuit of a standardized method to measure the ecological impact of fire. These bands were selected through a series of statistical tests evaluating Landsat band responsiveness to pre- and post-fire spectral changes. Near-infrared light is responsive to green or photosynthetic, reflecting highly in the presence of live biomass. Short-wave infrared, however, is responsive to soil and charred materials, reflecting highly over-exposed soil surfaces. Fire reduces live biomass while increasing soil exposure.

Quoting Key & Benson , dNBR is sensitive to the following fire effects:

1. Increasing char and consumption of downed fuels.
2. Increasing exposure of mineral soil and ash.
3. Change to lighter colored soil and ash.
4. Decreasing moisture content.
5. Increasing scorched-then-blackened vegetation.

The dNBR is a differencing technique requiring two images: one image prior to the burn with the second following the fire. One dNBR method, known as "initial", uses a Landsat image immediately following burning cessation. The second method, "extended", uses an image taken approximately one year following the end of the burn. Anniversary images are used to minimize phonologic and solar illumination variables.

The calculation of dNBR is straightforward. First, the Normalized Burn Ratio (NBR) for each image (i.e. pre and post) is found; calculated in units of "at satellite" reflectance which have been corrected for atmospheric transmittance.

$$NBR = \frac{R4 - R7}{R4 + R7}$$

R4 = Band 4, Near-infrared
R7 = Band 7, Shortwave Infrared

Next, the results are differenced to find the Differenced Normalized Burn Ratio. The final number is a unitless measure of the normalized change occurring in the bands. Values typically range from -550 to +1350. Following the differenced NBR calculation, the dNBR undergoes a signed 16-bit (value range of - 32768 to 32767) scaling to achieve the high dynamic range seen in the severity categories. Without the scaling, the value range possible given the formulation is -1 to +1.

$$dNBR = NBR_{prefire} - NBR_{postfire}$$

DNBR is mapped to burn severity using ground assessments measuring fire severity according to defined ecological impact parameters. The Composite Burn Index (CBI) was developed to identify links between the spectral changes observed in dNBR calculations to the ecological affects occurring at the burn site (see Key and Benson). Using CBI as a severity reference, dNBR values were assigned a severity class using cluster analysis to determine natural groupings. The dNBR severity classes used in this analysis are reported in Table 3. This is not the sole dNBR classification method. Other classifications using fewer categories have been proposed (see Epting).

Severity Level		DNBR Range
1	Enhanced regrowth, high	-500 to -251
2	Enhanced regrowth, low	-250 to -101
3	Unburned	-100 to +99
4	Low severity	+100 to +269
5	Moderate-low severity	+270 to +439
6	Moderate-high severity	+440 to +659
7	High Severity	+660 to +1300

Table 3. dNBR Severity Class Definitions. Severity classes were defined following an investigation of the relationships between post-fire ecological effects and dNBR response (from Key and Benson).

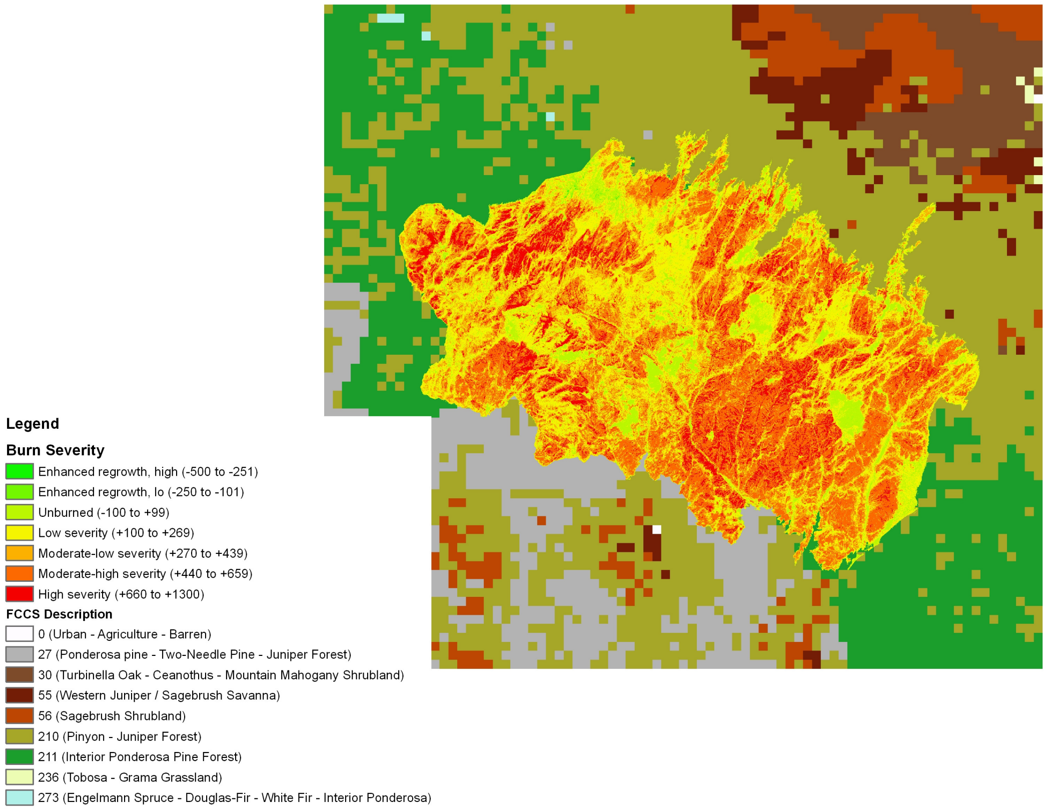

Figure 1. Example dNBR Map. The 2002 Rodeo fire overlayed on FCCS fuel beds. Note the spatial resolution disparity between the two layers (dNBR 30-m, FCCS 1-km).

Description of Terrain and Fuel Bed Variables

During the discussion of fire behavior, the chemical, physical, and physiological properties of fuel were determined to influence burn pattern, intensity, and severity. These three properties are all functions of environmental context and local ecological characteristics such as climate, vegetation, disturbance history, and terrain. Feedbacks among these characteristics are strong and identifying a single, overriding property most influential on fire is not possible. The goal in this analysis is not to describe fire severity and intensity comprehensively, but to search for measurable correlations in large-scale, consistent spatial datasets.

Vegetation is highly determined by landscape position (Agee, Finney and Gouvenain) relative to landforms and soils. Furthermore, live and dead fuel moisture, fuel loading, and fuel structure is also highly determined by these same terrain characteristics (Keane, Burgan and Wagtendonk). The four terrain variables used here (i.e. elevation, slope, aspect, and annual incident solar radiation) each have unique influences on vegetation and fuel moisture. Fuel moisture is a primary concern, though de-coupling terrain / fuel moisture from vegetation is not possible and by no means implied. However, terrain influence on fuel moisture is, in large part, related to ecological constraints placed on vegetation and, hence, is usable as surrogate measures of the fuel bed moisture content. Furthermore, terrain also places controls on the local microclimate (Burgan and Shasby).

Elevation is the distance, measured vertically, of the Earth's surface from a reference plane, often sea level. As elevation increases, temperature decreases according to adiabatic lapse rates roughly equivalent to 3.57°F per 1000 feet which is often accompanied by lower humidity and precipitation levels (Tveito and Forland). The physical structure of fuels changes with elevation as well. High elevation forest ecosystems have lower quantities of living biomass but often higher levels downed woody debris in fire suppressed systems (Tande). Decomposition rates occur at much slower rates and because of this fire is an important agent of internal carbon cycling. Fuels also have lower relative fuel moistures over time from lower precipitation and higher solar insolation with sparser canopies. The effects of elevation, in this study, are considered from internally consistent ecosystems. That is, the influences of elevation on fire intensity and severity have universal affects on fuel moisture, quantity, and structure regardless of forest type. It is hypothesized that higher elevations will have higher severity burns.

Slope measures the relative inclination of a surface from a reference plane often measured in percent or degrees. Slope primarily affects fire movement, altering flame orientation relative to nadir. As a result, fuels are warmed (and dried) more quickly in an upslope direction during a burn (Omi). Furthermore, vegetation is also affected by slope steepness as drainage patterns and soil structure change (Holland and Steyn). For slope, it is expected that faster moving fires result in lower severity burns. Hence, an increasing / steeper slope will result in lower severity.

Aspect describes a landscape position's orientation relative to an azimuth – typically north. For example, due north is recorded as 0 or 360 degrees, south measured as 180 degrees. The amount of solar energy varies according to the orientation of the landscape. As a result, southern-facing aspects are generally warmer with higher amounts of live biomass. It is expected that more southern-facing slopes have higher severity.

Annual incident solar radiation (watts/meter^2/year) is a yearly average of solar energy received by an area at a particular elevation, slope, and latitude (McCune and Keon). Although very similar to aspect on cursory examination, annual incident solar radiation provides a time-averaged perspective on potential annual solar radiation. It is calculated using a combination of slope, latitude, and folded aspect empirically calibrated to match Buffo and Murphy measure of potential direct incident radiation. Annual incident solar radiation is calculated as follows:

$$Rad = 0.339 + 0.808*\cos(L)*\cos(S) + -0.196*\sin(L)*\sin(S) + -0.482*\cos(A)*\sin(s)$$

Rad = radiance (watts/meter^2/year)
L = latitude (radians)
S = slope (radians)
A = folded aspect

It is expected that as annual incident solar radiation decreases, fire severity will decrease.

Terrain variables affect fuel condition (e.g. moisture, loading) by altering the mechanisms driving the deposition, distribution, and moisture cycling in fuel beds. Implied is the dominant influence of climate and weather variability with the terrain variables providing topographic controls (Burgan and Shasby). However, it is the fluctuations in weather conditions within the two weeks prior to ignition that most greatly influence fire intensity and severity as fuel moisture fluxes change rapidly according to external conditions (Bradshaw et al.). The goal of this analysis is to establish surrogate controls on the fuel environment to establish a link between severity and intensity. Fuel moisture models, the National Fire Danger Rating System for example, model fuel moisture fluxes at small temporal scales utilizing terrain and local weather to predict moisture content and fire threat. Unfortunately, fuel moisture predictions generated by these process-based models are not at a resolution commensurate with dNBR data due mostly to the sparity of weather data collection stations.

The data used here are available at a spatial scale consistent with remotely sensed data. Landsat dNBR products and DEMs are both available at 30-meter spatial resolution. For each fire, the same terrain variables can be generated. Weather data are available at sparse scales. Coupling terrain models with accurate estimation of weather patterns would yield interesting results aiding the utility of dNBR in informing fuel moisture and fire danger models. Creating data of an equivalent resolution requires weather data interpolation to a much higher spatial resolution. The errors associated with this interpolation are high, the uncertainty of any interpolated point nearly equivalent to the reference data variance.

Chapter 3. Data Sources

Burn severity data grids and fire perimeter shapefiles were downloaded from the USGS's Monitoring Trends in Burn Severity (MTBS [formerly Burn Severity Mapping Project]) data distribution website (USGS "Monitoring Trends in Burn Severity (Mtbs)"). These downloads occurred approximately from May 2006 to June 2006. All 89 fires available on the website at that time were acquired and incorporated into a GIS for visual examination. In some cases, fires had both initial and extended dNBR assessments. In these cases, initial dNBR calculations were chosen to match the majority of fires having no extended assessment. Since 2006, MTBS has added additional fires but no attempts to update this analysis with the new fires occurred for this study. Digital elevation models (DEMs) for each fire were acquired from the USGS (USGS "Usgs Geographic Data Download"). Areas of interest for each fire were identified by finding perimeter coordinates of the burn area and using these as spatial references for the data download. The FCCS (Fuel Characteristic Classification System) from which the fuel bed summary was derived was downloaded from the U.S. Forest Service's FERA (Fire and Environmental Research Application) website (USDA). The FCCS is fuel bed map developed by FERA at 1-km classifying fuel types according to primary vegetation and fuel loading. Only the fuel type was summarized for the FCCS fuel layer.

Data Processing

Spatial processing used a combination of ArcGIS, Python, and MatLab. These three software packages allowed strong spatial and statistical integration and rapid iteration through datasets: ArcGIS provided spatial analysis and visualization, Python the iteration of GIS processing, and MatLab the statistical tools.

Selected dNBR images underwent a three step filtering process:

1. Images were visually assessed to check for errors and also ensure the file itself was not corrupt.
2. dNBR pixels were classified according to their severity class (refer to Table 3 for class delineation) to create thematic dNBR maps.
3. A screening algorithm was run on the fires to select those with dNBR representation in each category not differing by greater than 50%. By this method, extreme sample size disparities and unrepresented severity classes were unlikely. This filter becomes important when spatial autocorrelation is discussed.

Slope, aspect, elevation, annual incident solar radiation, and spatial coordinates were then calculated for each dNBR cell. Through a series of overlays and data type transformations (e.g. GIS shapefile to test file), point files containing these attributes were created. An excerpt from an example fire is located in Appendix A. Tabular data from each fire were then exported to text files and imported into MatLab for the rest of the analysis. Figure 2 contains a flow chart depicting the analysis process containing the GIS procedure used, the program involved, and intermediate outputs.

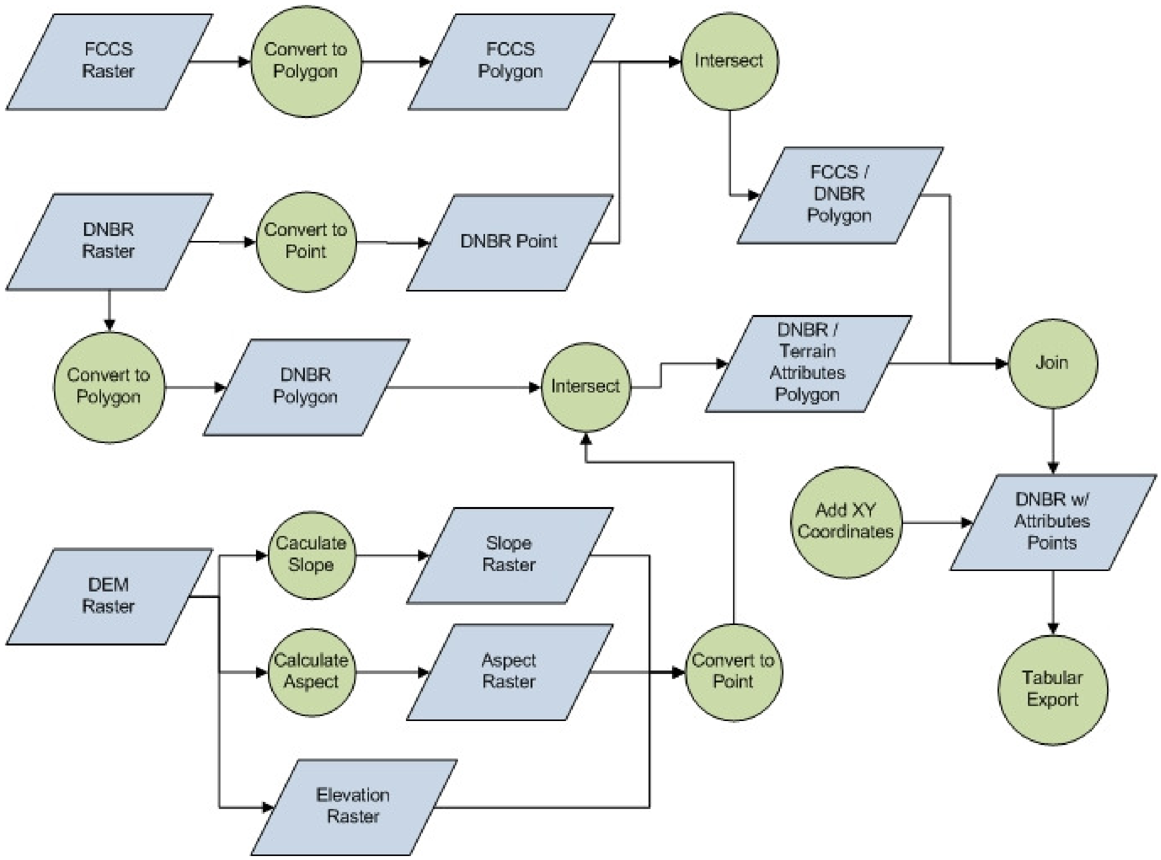

Figure 2. GIS Analysis Flow Chart.

Statistical Procedures

Parametric statistics contain assumptions regarding the underlying distribution of the sample datasets. Before normality tests could be run, the datasets were tested for spatial autocorrelation. Spatial autocorrelation occurs when data is spatially interdependent – the degree of correlation between data points is related to the distance between the data points. Spatial autocorrelation gives more significance to results than data justifies (Dalte and Fortin). The primary reason for the increase in significance derives from the false assumption in spatially autocorrelated data that errors are independent. In a general sense, when data are positively spatial autocorrelated, *n* observations are not truly *n* observations when analyzed using traditional statistical techniques (Cliff and Ord). Accounting for spatial autocorrelation is dependent on the nature of the analysis. It may be the case that the reasons for spatial autocorrelation is the focus of the statistical study.

A variogram using all dNBR values was calculated to assess spatial autocorrelation in the dNBR datasets. A variogram quantitatively calculates data variance based on spatial relationships (Rossi et al.). Two important features of spatial correlation structure can be gleaned from the variogram. The *sill* is the overall variance of the dataset while the *range* is the maximum distance between two data points where correlation still occurs (often called the "correlation length" or "spatial lag"). The dNBR data exhibited a spatial lag of ~1.5 km when averaged across all fires. Hence, data points that fall within a 1.5 km straight-line distance of each other have underlying spatial correlation.

A number of methods have been proposed to deal with spatially autocorrelated data (see for example M. R. T. Dale et al.). A method similar to Ostendorf and Reynolds in which data were selected randomly from the data pool and the distance between sample points always exceeded the spatial lag requirement. To accomplish this, a data selection algorithm was written to "walk" through the data selecting points at a specified spatial lag. In addition, selected dNBR severity classes are evenly distributed within 50%. The algorithm is iterative, first creating a dataset that matches the lag requirement and checking the proportionality of the severity classes. If the proportionality requirement is not met, the created dataset is thrown out and another created.

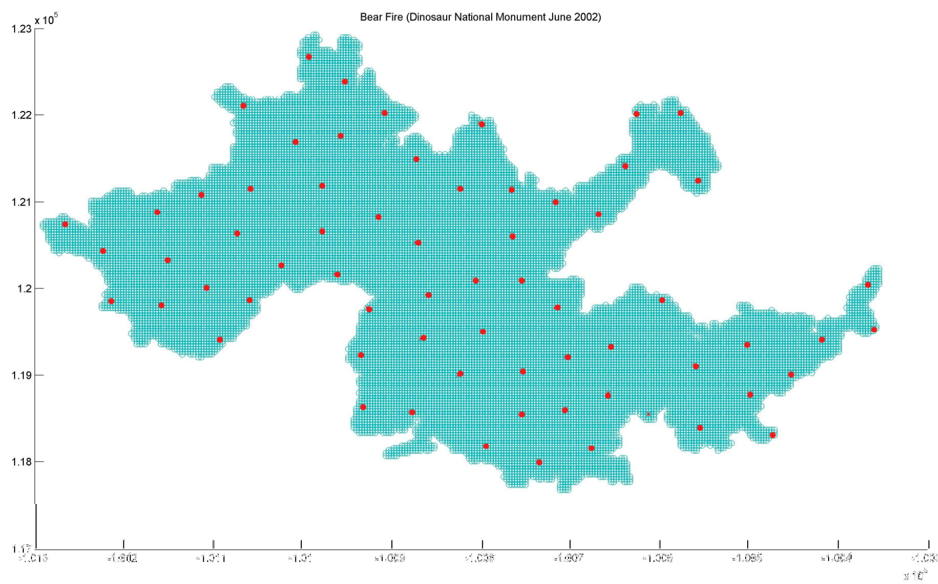

Figure 3. Example Output from Point Selection Algorithm. A reduced spatial lag (500 m) for the point selection algorithm resulted in more internal fire pixel selection. The original lag, 1.5 km, selected points falling on the fire edge.

After test runs of the algorithm using a 1.5 km spatial lag, it was discovered the data points selected all fell along fire perimeters. These selected points seemed unacceptable considering all dNBR values may be subject to uncertain edge effects. Furthermore, the subjectivity associated with the delineation of fire perimeters could lead to selected pixels falling outside the burned area altogether. Lag was adjusted to 500 meters to compensate for this uncertainty. The dNBR results were much more favorable as the points selected were distributed more homogenously not neglecting internal fire variability (see Figure 3). The trade-off of lowering the spatial lag and incorporating greater autocorrelation is not expected to detrimentally affect the analysis. Furthermore, it is not expected that every fire would exhibit the same degree of spatial autocorrelation.

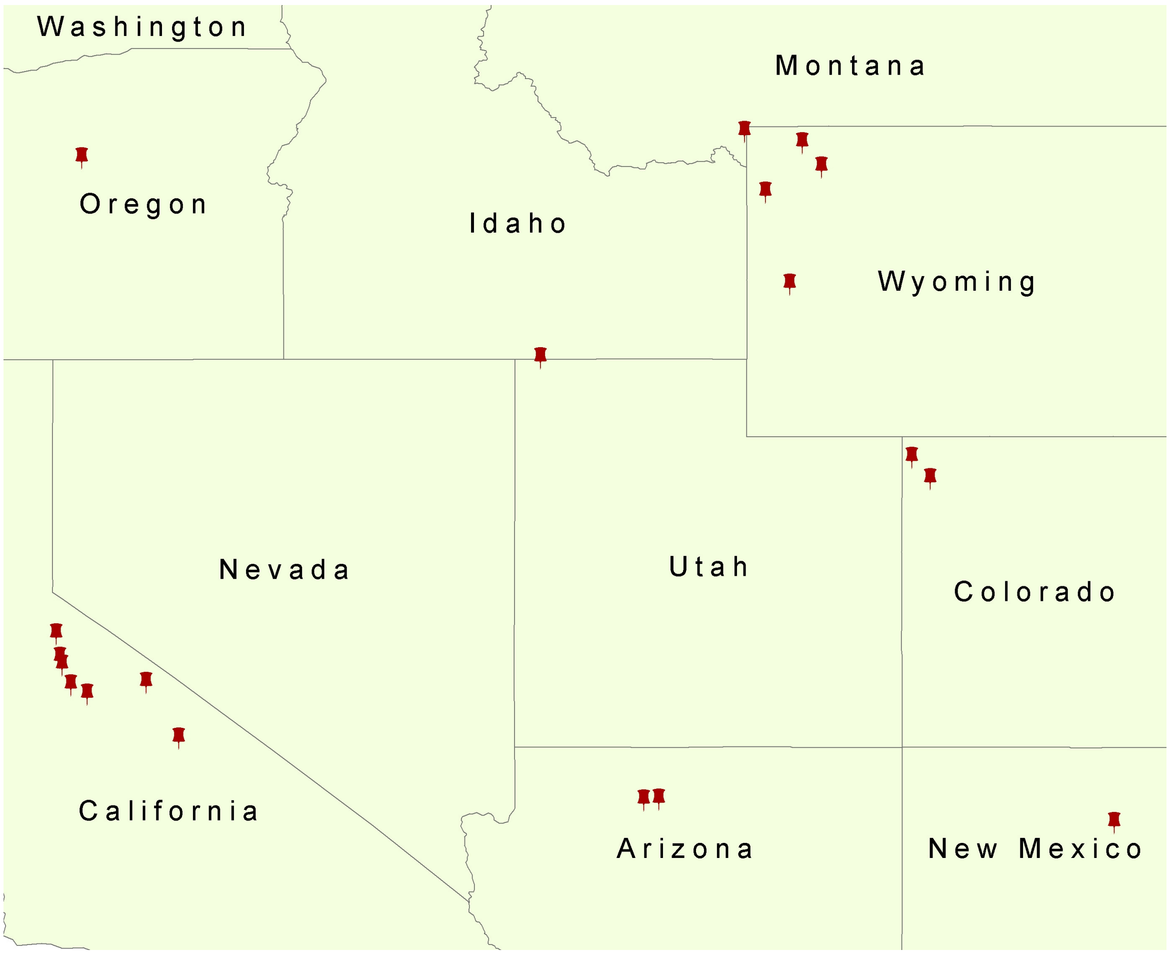

Figure 4. Map of Fire Locations. Selected fires occurred in eight different states from 1998-2003. The heavy wildfire season of 2002 and 2003 are heavily represented in California.

Overall, nineteen fires out of 89 met the severity class distribution and spatial lag requirements. These fires burned during the years 2002 – 2004 (with exceptions in 1998 and 2004) in the states of Wyoming, Colorado, Idaho, California, Oregon, Arizona, and New Mexico. Table 4 lists fires and start dates with Figure 4 containing a map of fire locations. Most area burned occurred in Lodgepole pine forests; the second occurring in Pinyon-Juniper forest types. Ponderosa pine was also heavily represented. Smaller occurrences of deciduous forest types (e.g. Oak, Douglas-fir) were often in mixed coniferous-deciduous stands. For the statistical sample, Appendix D contains burn severity class summaries by fuel type.

Higher severity fires tend to occur in Lodgepole pine ecosystems (Agee "The Landscape Ecology of Western Forest Fire Regimes"). Crown fires are common in Lodgepole pine as the linear fuel structure and longer fire interval intervals increase canopy fire occurrence. The combination of larger, more intense fires increases biomass consumption during these burns hence higher severity. Ponderosa pine, for example exhibits a more low to moderate fire severity regime. Fire return intervals in this forest type are shorter and fires tend to stay on the ground and in the understory creating a patchwork of fuel availabilities. However, fire suppression during previous decades has led to fuel build-ups similar to Lodgepole ecosystems increasing fire intensity and severity in these forest biomes (Brown, Kaufmann and Shepperd).

Fire Name	State	Total Area (km)	Samples	Latitude	Longitude	Start Date
Arthur	Wyoming	16.7535	62	44.46	-110.08	7/29/2001
Bear	Colorado	20.3697	68	40.45	-108.68	6/27/2002
Boundary	Wyoming	26.9235	100	44.14	-110.81	8/15/2000
Broad	Wyoming	33.2352	104	44.77	-110.33	6/27/2002
Buster Flat	Colorado	35.9253	70	40.72	-108.92	7/3/2000
City of Rocks	Idaho	58.9275	177	42.00	-113.71	8/18/2000
Dexter	California	10.5957	37	37.82	-118.79	9/2/2003
Fuller	California	28.1547	72	37.11	-118.37	7/12/2002
Gin Flat	California	28.2816	103	37.79	-119.76	9/27/2002
Kibbie Complex	California	29.0916	94	38.05	-119.87	7/29/2003
Meadow	California	23.4225	70	37.67	-119.55	6/27/2004
Middle Mountain	Oregon	13.5261	21	44.58	-119.62	9/23/2002
Mountain Complex	California	17.8983	55	38.15	-119.90	7/20/2003
Mud	California	18.531	57	38.45	-119.95	8/31/2003
Mule	Wyoming	13.8195	46	42.95	-110.50	7/10/2002
Oso Complex	New Mexico	37.9422	107	36.02	-106.32	6/20/1998
Poplar and Big	Arizona	33.4881	104	36.32	-112.18	9/5/2003
Powell	Arizona	15.9561	51	36.31	-112.38	6/15/2003
Rathbone	Montana	95.4	294	44.92	-111.08	8/20/2003

Table 4. Fire Locations and Start Dates.

Two statistical hypothesis tests were used to evaluate dNBR and terrain relationships. The null hypothesis, in each case, states that no significant relationship (95% confidence) exists between the datasets. The linear regressions test for co-linearity between two continuous variables uses residual differences to evaluate the linear model fit (Zar). For this test, the raw dNBR values were tested against the raw terrain values. Analysis of Variance (ANOVA) uses a grouping variable to evaluate the likelihood of mean overlap amongst continuous predictors using the data subset variances. In the ANOVA case, the severity class was used as the grouping variable to evaluate the mean differences of the terrain variables within the severity classes. However, when aspect was tested, the aspect class was used as the grouping variable and mean differences in raw dNBR was the dependent variable.

After data point selection, the statistical analysis proceeded as follows:

1. Descriptive statistics for each analysis variable were calculated.
2. Data distributions were evaluated for normality and transformed when necessary to meet parametric statistical assumptions.
3. Regression statistics for each continuous predictor were evaluated with dNBR.
4. Continuous variables were then evaluated utilizing dNBR reclassed into severity categories with ANOVA.

Implementing a categorical assessment of dNBR as opposed to a continuous assessment is the most reasonable method to measure terrain influences on severity. First, dNBR severity designation is a qualitative process and the actual continuous dNBR values has no physical meaning. Grouping the data accounts for the implicit uncertainty in assigning a quantitative value to a qualitative measure of fire severity. Second, considerable noise is expected to have entered the dataset in the form of georegistration errors (i.e. pixel shifting) and generic errors during initial calculations. Grouping the data into classes minimizes the effects of outlier data originating from one of these two sources. However, the informed sampling utilized in the sample selection should also minimize these uncertainties. The data distributions themselves were transformed using logarithmic and power transformations to approximate normal.

Chapter 4. Results

Results for each test are discussed below. Tests are segmented by predictor variable and test variety (i.e. linear, categorical). Each categorical result is also accompanied by a mean confidence graph representing the behavior of each severity grouping.

For the categorical results, we considered significance at the 0.05 level. Ninety-five percent confidence levels for the mean differences are shown in the lower and upper columns for each severity class pair. Confidence intervals that do not contain zero represent groupings with statistically significant mean differences. Tables containing the categorical results have significant mean differences highlighted.

Slope coefficients, intercepts values, *r*-squared and *p* statistics for the linear regressions are also contained in tables. A 95% confidence interval was used to determine significance in all cases. A regression was performed for each dNBR / terrain combination except aspect as no continuous representation of aspect was used. Multiple comparison plots for each ANOVA are located in Appendix B.

Elevation

Categorical

Severity Class		Lower	Mean Difference	Upper
4	5	-22.3136	33.5045	89.3226
4	6	-83.8207	-16.9451	49.9305
4	7	-287.516	-206.8817	-126.2475
5	6	-124.3962	-50.4496	23.497
5	7	-326.9751	-240.3862	-153.7974
6	7	-284.034	-189.9366	-95.8392

Table 5. Categorical Results for Elevation. Significant differences occurred between high severity (class = 7) burning and all other severity classes. Other severity classes showed little to no variation.

Linear

Intercept	Slope	r-squared	p
2.4	-0.5	0.0028	< 0.01

Table 6. Linear Results for Elevation. Very low linear correlation is observed in the data.

Slope

Categorical

Severity Class		Lower	Mean Difference	Upper
4	5	-0.4686	-0.3597	-0.2508
4	6	-0.4085	-0.2781	-0.1476
4	7	-0.34	-0.1827	-0.0254
5	6	-0.0627	0.0816	0.2259
5	7	0.0081	0.177	0.3459
6	7	-0.0882	0.0954	0.279

Table 7. Categorical Results for Slope. Low severity (class = 4) fire pixels occurred on shallower slopes with significant differences from all other severity classes. The significant difference between severity class 5 and 7 is slight. Interestingly, slope decrease as severity increases from class 5 to 7.

Linear

Intercept	Slope	r-squared	p
3.1	-2.5	0.0299	< 0.01

Table 8. Linear Results for Slope. A negative correlation was observed.

Aspect

Severity Class		Lower	Mean Difference	Upper
N	NE	-0.0111	-0.0001	0.011
N	E	-0.0159	-0.0049	0.0061
N	SE	-0.0171	-0.0068	0.0034
N	S	-0.0178	-0.0074	0.0029
N	SW	-0.0169	-0.0062	0.0044
N	W	-0.0209	-0.0105	-0.0001
N	NW	-0.0138	-0.003	0.0079
NE	E	-0.0155	-0.0048	0.0058
NE	SE	-0.0167	-0.0068	0.0031
NE	S	-0.0174	-0.0074	0.0026
NE	SW	-0.0165	-0.0062	0.0042
NE	W	-0.0205	-0.0104	-0.0004
NE	NW	-0.0134	-0.0029	0.0076
E	SE	-0.0118	-0.0019	0.0079
E	S	-0.0125	-0.0025	0.0074
E	SW	-0.0116	-0.0013	0.0089
E	W	-0.0156	-0.0056	0.0044
E	NW	-0.0085	0.0019	0.0124
SE	S	-0.0098	-0.0006	0.0086
SE	SW	-0.0089	0.0006	0.0101
SE	W	-0.0128	-0.0037	0.0055
SE	NW	-0.0058	0.0039	0.0136
S	SW	-0.0084	0.0012	0.0108
S	W	-0.0123	-0.003	0.0062
S	NW	-0.0053	0.0045	0.0143
SW	W	-0.0139	-0.0043	0.0054
SW	NW	-0.0069	0.0033	0.0134
W	NW	-0.0023	0.0075	0.0173

Table 9. Output Statistics for Aspect. Aspect classes showed little differentiation. Significant differences were very slight with mean variance separation nearly coincident.

Annual Incident Solar Radiation

Categorical

Severity Class		Lower	Mean Difference	Upper
4	5	0.0012	0.0138	0.0265
4	6	-0.0013	0.0138	0.029
4	7	0.024	0.0423	0.0605
5	6	-0.0168	0	0.0167
5	7	0.0088	0.0285	0.0481
6	7	0.0072	0.0285	0.0498

Table 10. Categorical Results for Annual Incident Solar Radiation. Annual incident radiation tended to decrease as severity increased. Many of the observed mean differences are significant.

Linear

Intercept	Slope	r-squared	p
0.9	0.2	0.0088	< 0.01

Table 11. Linear results for Annual Incident Solar Radiation. Slight positive linear correlation.

Results Summary

- High severity fires occurred at higher elevations with little variation occurring in lower severity classes.
- Low severity fires occurred on shallower slopes with a decreasing, stair-step pattern as severity increased (i.e. as slope decreased, severity increased).
- Severity and aspect appear to have no statistically strong relationships with an apparent random patterning appearing in the data.
- As severity increases, there is a slight decrease in annual incident solar radiation.
- All linear tests were significant but the low coefficients of determination indicate little of the overall data variance was explained.

Chapter 5. Discussion

Overall, the statistical tests presented mixed results with regressions revealing little and categorical statistics displaying interesting patterns that, in many cases, went against hypothesized relationships. Interpreting categorical results is challenging as the statistical measures group mean differences and considerable overlap due to data variance occurred between groups. The considerable internal variance of the datasets leads to the fairly certain conclusion that this analysis has identified broad, mild trends relating terrain and burn severity. Due primarily to the complex nature of fire and ecosystem dynamics, this analysis has also identified the possible importance of incorporating timely and relevant data (i.e. weather, fuel condition) to better understand the dNBR fire severity measure.

Linear Correlations

While linear tests did prove significant, all coefficient of determination values were below 0.1 indicating a poor model fit. Scatter plots (Appendix C) also show no linear trends. Within this dataset, severity cannot be tied to terrain on a pixel-by-pixel level suggesting the controls on severity primarily rest in the fuel bed structure, weather-related fuel moisture fluxes, and vegetation type and condition expressed broadly across terrain pattern. However, it is also possible that the fine-scale used in this analysis encapsulates unnecessary noise related to georegistration and data collection errors. Resampling the data to a lower spatial resolution (i.e. 90 / 120 meter) may have a similar effect as the categorical grouping revealing continuous relationships otherwise shadowed by fine-scale noise.

Interpretation of Categorical Results

Elevation, slope, and annual incident solar radiation had statistically significant differentiation when grouped by severity class. As mentioned above, the data variance for each subset was very high with considerable overlap in all burn severity categories. Furthermore, with the exception of solar radiation, negative and / or positive trends were ill-defined and decidedly sporadic. With the absence of linear correlations, it is possible to conclude that terrain, as measured here, is not a significant control on severity and logically then does not strongly affect fuel moisture. These results do indicate terrain is controlling some “aspect” of fire severity that is likely more ecological than physical. It is possible, however, to draw some useful information regarding the dNBR severity metric and its sensitivity to pre-fire ecological condition.

Mean fire severity was greater in higher elevation burn areas. As mentioned previously, not all high elevation burn pixels exhibited enhanced severity; the variance overlap (including outlying severity pixels) shows near complete representation of severity values in all elevation classes. Three possible interacting ecological conditions help explain the phenomenon of higher mean severity in elevated areas: (1) lower decomposition rates increases the prevalence of downed woody debris, (2) lower relative humidity decreases fuel moisture in floor fuels, and (3) less live biomass in the canopy and lower litter deposition rates and thinner soils. The dNBR signature is sensitive to changes in live biomass and increased soil exposure – floor debris are consumed more completely as well as greater consumption of the lower proportioned live biomass.

The data revealed an interesting stair-step pattern occurring between fire severity and terrain slope. Overall, there was little mean differentiation in fire severity, but the data appears to indicate lower severity on shallow slopes. It is difficult to discern if the inverse severity / slope pattern (i.e. increasing severity with decreasing slope in severity classes 5, 6, and 7) has real significance. However, if it is significant, the result is *not* contrary to the hypothesized relationship between fire behavior and sloping terrain. The increased angle of flaming would result in a more rapidly moving fire. Fire temperature and intensity would lower the amount of biomass consumed and this decreased consumption registers in the remotely sensed dNBR signature. In addition, it is this slight mean adjustment that registers in large datasets. A smaller dataset focused on an isolated fire may not isolate this pattern and demonstrate no severity class differentiation.

A slight mean decrease in annual incident solar radiation from low to high severity fire pixels was detected. There was little overall mean differentiation between the fire severity classes. Similar to elevation, the vegetational gradient associated with the sun's potential energy, landscape position, and latitude affect the quantity of live biomass, microclimate, and decomposition rates. It may be expected that greater drying associated with more solar radiation would increase severity; however, this metric is a yearly average with insufficient temporal resolution to discern individual drying and wetting events. The quantity of live biomass, condition / amount of down woody debris, and forest litter depth associated with annual incident solar radiation seem to drive its relationship with dNBR.

Aspect results revealed slight relationships among severity patterns associated with the position of the landscape and incoming solar radiation at various times throughout a daily solar cycle. Severity was slightly lower on northerly facing slopes and slightly higher on western facing aspects. Northern aspects have generally lower temperatures through the growing seasons decreasing overall potential biomass (Holland and Steyn). The western facing slopes have higher seasonal growing temperatures receiving solar radiation during the warmest times of the day. It is possible the dNBR signatures retrieved following a fire were related to fuel moisture during the burn, but separating the biomass quantity and structure from its moisture content is difficult when the same external environmental factors affect both equally.

Multivariate and Nonlinear Statistics

In addition to the linear and categorical statistics reported here, multivariate approaches were also investigated which included multivariate regressions, classification trees, and regression trees. Following the results of the linear tests and qualitative examinations of the scatter plots, results from these multivariate approaches were not expected to yield significant statistical correlations and that was the case for the reasons presented above; primarily as a result of the much improved hypothesis testing yielded by the categorical examinations. Nonlinear trends observed in the categorical statistical results were not replicated through nonlinear regressions due to the substantial noise inherent in the non-categorical data.

Ecological Effects of Terrain

Categorical results indicate mean trends in dNBR fire severity across multiple terrain metrics. However, difficulty is encountered when attempting to interpret the observed severity effects as changing fuel moisture levels. If a strong linear relationship was found between dNBR and any terrain metric, perhaps a more potent argument for a fundamental fuel moisture / dNBR correlation could be constructed. Such a result would demand an additional explanation, other than a steep change in fuel availability and structure, answerable only when *direct* measures of fuel moisture, terrain, and dNBR can be statistically evaluated. In the absence of such a result, the categorical statistics are measuring broad trends with little relevance to an isolated terrain and dNBR pixel, especially when severity class terrain variance is considered.

The results found here are not contradictory with other statistical studies of dNBR, terrain, and weather data. For example, Collins et al. in a study utilizing regression trees to assess the relative influence of fuel availability, weather conditions, and topography on dNBR severity, correlation values were relatively low for each input and together, the predictor variables performance was again unsatisfactory in explaining overall dNBR variance. While these studies are important steps in understanding dNBR response to environmental and ecological conditions, answering the question of dNBR response relating to fuel consumption during burning is difficult without empirical fuel moisture data (or spatially explicit weather data commensurate with dNBR spatial resolution) at the time of burning. Currently, the spatial resolution of weather data is much lower than dNBR – Landsat-measured dNBR having a 30-meter resolution with weather data available on a scale of kilometers, highly variant from location to location.

Overriding the effect of terrain on fuel moisture is the effect of terrain on the local ecological conditions and, hence, growth, deposition, and decomposition on fuel types. Discerning the relative effect of each on a fire's behavior effect is nearly impossible. In essence, terrain is a useful surrogate measure, but a surrogate measure of multiple fire factors. Interpreting a diffuse measurement often leads to the conclusion that more refined data with less covariance potential is required. Important, however, is the conclusion that dNBR is not overly sensitive to the terrain effects on remote sensing; terrain can alter the radiative intensity of the return signal by changing the incidence angle of incoming radiation (Lillesand, Kiefer and Chipman). In other words, terrain is insufficient in explaining the overall variability of the dNBR metric.

Chapter 6. Conclusion

Mean topographic effects on dNBR are measurable across multiple forest biomes and burn types. The absence of linear correlations suggests the variability across topographic gradients is related to terrain influences on vegetation, fire behavior, and fuel moisture. Differentiating with any precision the exact influence topography has on severity is limited by the spatial resolution of empirical data that can directly measure factors important to informing consumption models such as fuel moisture, precise fuel density, smoldering, and burn intensity. The results reported here indicate topography captures a myriad of these fire characteristics:

1. High elevation areas burn more severely suggesting fuel structures encouraging canopy fires with more fuel consumption.
2. Decreasing slope with increasing severity suggests fire behavior, particularly the speed of the flaming front, appears in the dNBR measure.
3. Increased annual incident radiation may increase biomass lowering the fuel consumption and ecological impacts typical to less ecologically active areas (i.e. high elevations).

Future Research

Interpolating weather data (e.g. relative humidity, temperature, wind speed) accurately to a scale commensurate with the dNBR maps would provide interesting fodder for statistical correlation tests. Identifying specific dNBR correlates that also feed into consumption models is an ideal result from such an analysis. Another important question not investigated in this thesis is the relationship of dNBR with specific fuel types systems such as FCCS fuel beds. Utilizing independent variables with fewer possible effects on fire behavior and intensity than topography will ease the interpretive process and offer insight into the inclusion of dNBR in consumption models.

Appendix A. Example Fire Data Table.

X-coord	Y-coord	DNBR Severity Class	DNBR	Aspect	Slope %	Elevation (m)	FCCS Code	Annual Incident Radiation	Aspect Class
-1121920.972	603591.3006	5	355	159.8436	11.9272	2521.3289	22	0.9717	5
-1115380.972	585921.3006	6	449	237.6529	0.4869	2493.1292	22	0.9199	6
-1100470.972	595521.3006	5	408	355.3427	1.9661	2587.0532	22	0.8974	1
-1123000.972	601131.3006	6	501	299.3283	13.1024	2361.4109	52	0.8193	8
-1100320.972	594711.3006	6	655	348.7125	1.521	2615.3992	22	0.9025	1
-1098970.972	595491.3006	4	116	132.9901	8.0477	2574.7769	22	0.9401	4
-1099540.972	594411.3006	7	731	58.2111	4.2954	2592.1521	59	0.888	2
-1099960.972	595311.3006	6	612	320.9727	1.1991	2605.865	22	0.9081	8
-1122820.972	600531.3006	6	652	209.8437	4.8413	2462.1853	52	0.9406	6
-1113940.972	587301.3006	4	221	156.6969	7.3781	2519.7498	52	0.9534	4
-1113550.972	587661.3006	4	149	118.7425	21.8638	2495.6619	52	0.9127	4
-1114630.972	585171.3006	6	556	134.4679	22.107	2406.0486	22	0.9519	4
-1123240.972	598401.3006	6	590	52.241	26.0062	2317.1287	52	0.6709	2
-1099390.972	595191.3006	7	906	76.9106	2.7013	2589.9023	22	0.9067	3
-1121740.972	600711.3006	4	265	249.0094	0.7051	2476.3462	22	0.9193	7
-1111210.972	587601.3006	4	150	218.2282	7.2842	2607.73	22	0.9449	6
-1116670.972	585831.3006	4	178	189.4676	10.8143	2462.2	22	0.9722	5
-1100020.972	593541.3006	7	689	123.5276	2.8708	2616.4788	22	0.9246	4
-1122040.972	602061.3006	6	444	285.3479	3.6577	2505.4824	22	0.9009	7
-1122760.972	599511.3006	4	239	216.6647	5.9409	2335.9675	22	0.9417	6
-1114660.972	586221.3006	7	781	124.0779	8.1126	2467.2632	22	0.9319	4
-1115290.972	586791.3006	4	219	228.5755	0.3767	2525.3499	22	0.9201	6
-1122040.972	599451.3006	5	301	228.9212	13.2341	2434.418	52	0.9447	6
-1120660.972	601281.3006	4	234	176.7834	3.8003	2507.1885	52	0.9405	5
-1116100.972	586041.3006	4	111	266.9879	4.6572	2482.8787	22	0.9079	7
-1116100.972	586731.3006	4	147	277.0506	2.425	2500.6414	22	0.9101	7
-1116670.972	586641.3006	4	199	288.8694	0.5833	2483.6216	22	0.9159	7
-1122310.972	601491.3006	7	707	304.3655	4.5605	2460.3279	52	0.8846	8
-1113910.972	586551.3006	4	133	105.0349	23.7777	2369.3257	22	0.865	3

Appendix B. Multiple Comparison Plots for ANOVA Tests.

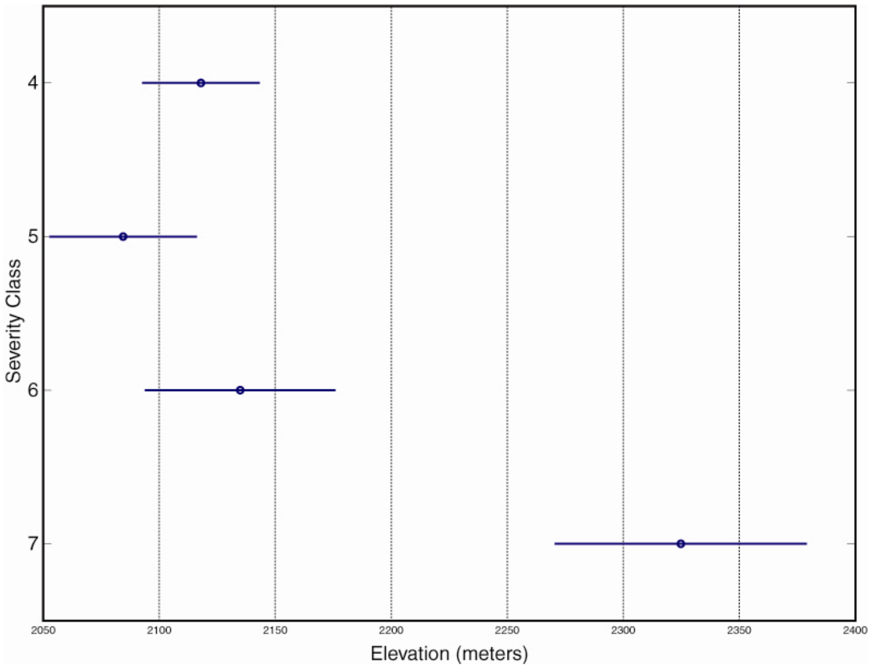

Figure 1. Elevation Multiple Comparison Plot.

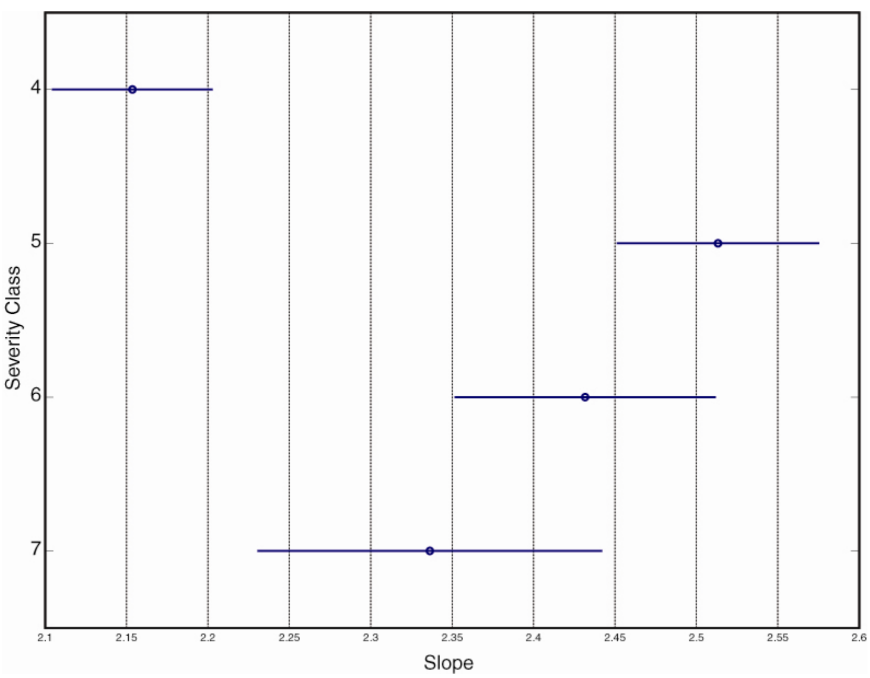

Figure 2. Slope Multiple Comparison Plot.

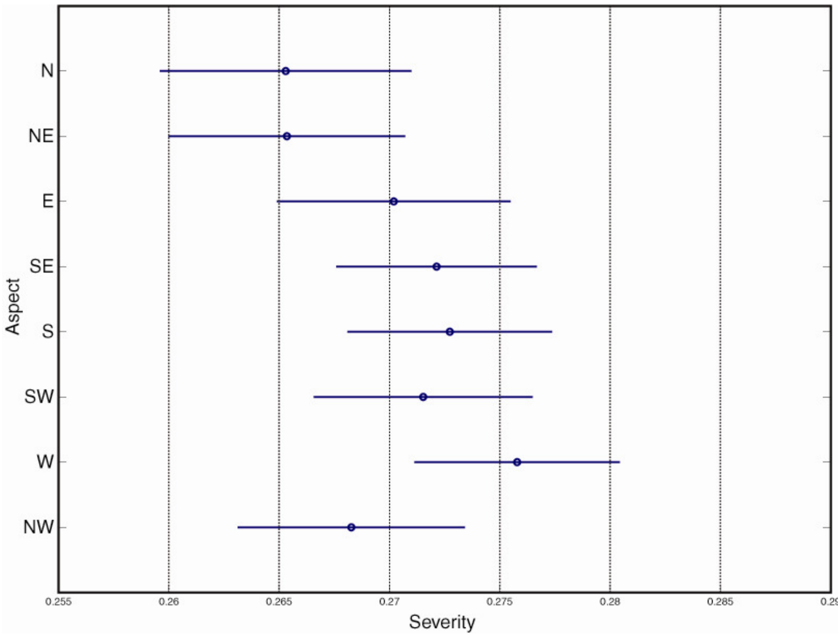

Figure 3. Aspect Multiple Comparison Plot.

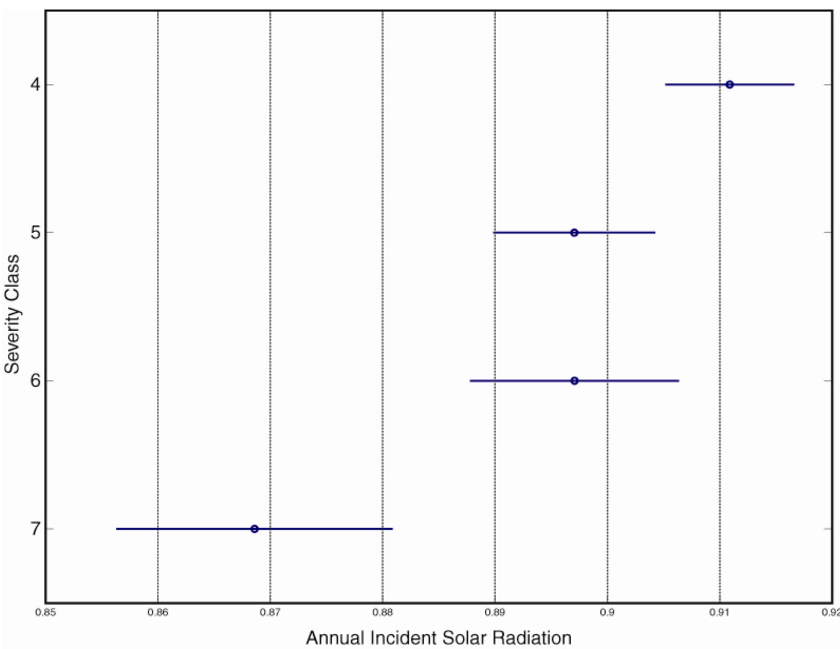

Figure 4. Annual Incident Solar Radiation Multiple Comparison Plot.

Appendix C. Regression Scatter Plots.

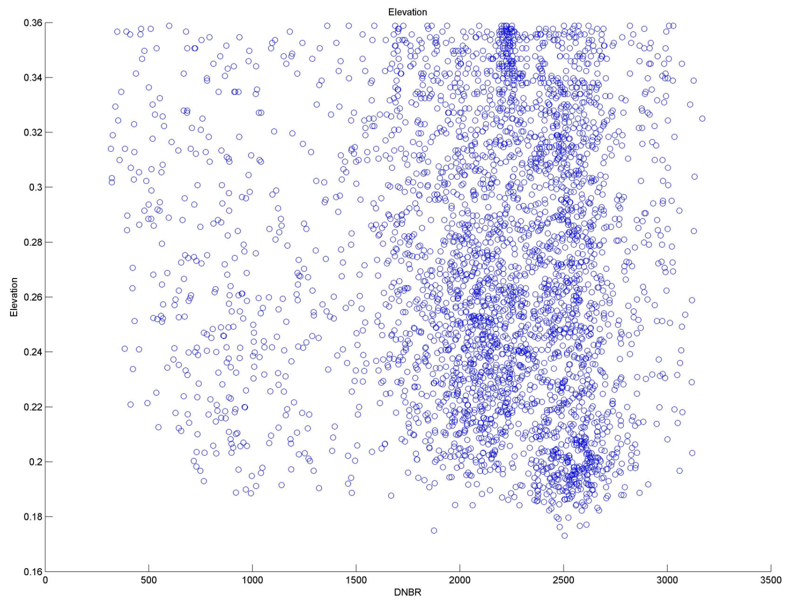

Figure 5. Elevation Scatter Plot.

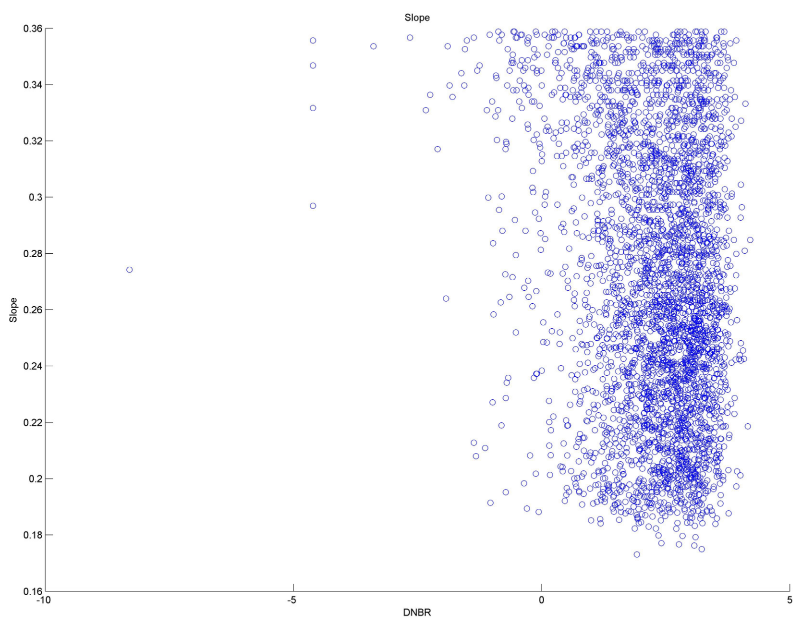

Figure 6. Slope Scatter Plot.

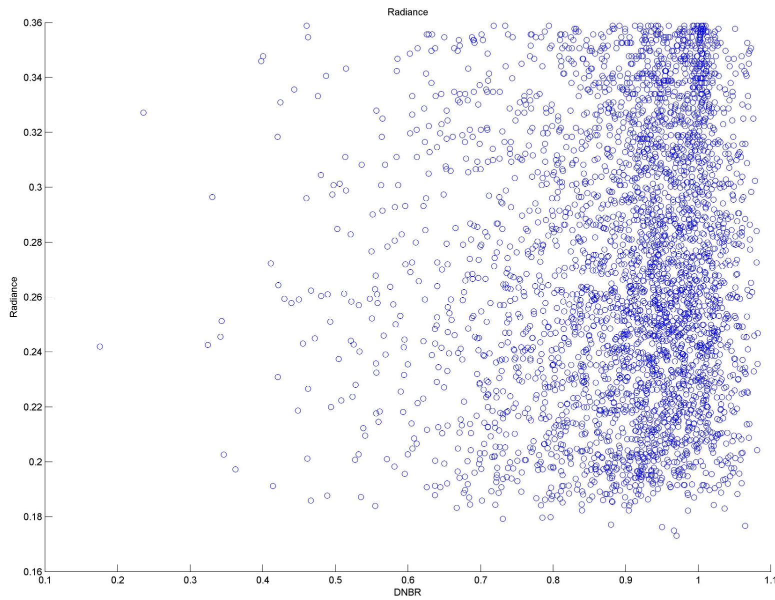

Figure 7. Annual Incident Solar Radiation Scatter Plot.

Appendix D. Fuel summary by FCCS Fuel Bed.

Fuel Description	Scientific Name	4	5	6	7	Grand Total
Trembling aspen forest	*Populus tremuloides*	0.81	0	0	0	**0.81**
Trembling aspen / Engelmann spruce forest	*Populus tremuloides / Picea engelmannii*	0	0.81	0	0.81	**1.62**
Vaccinium - Heather shrublands	*Vaccinium* L.	0.81	0.81	0.81	0	**2.43**
Mountain hemlock - Red fir - Lodgepole pine - White pine forest	*Tsuga mertensiana / Abies magnifica / Pinus contorta / Pinus albicaulis*	1.62	3.24	0	0	**4.86**
Engelmann spruce - Douglas-fir - White fir - Interior ponderosa	*Picea engelmannii / Pseudotsuga menziesii / Abies concolor / Pinus Ponderosa*	4.05	3.24	0	0	**7.29**
Red fir forest	*Abies magnifica*	6.48	1.62	1.62	0	**9.72**
Showy sedge - Alpine black sedge grassland	*Carex spectabilis / Schoenus nigricans*	4.05	2.43	1.62	1.62	**9.72**
Subalpine fir - Lodgepole pine - Whitebark pine - Engelmann spruce	*Abies lasiocarpa / Pinus contorta / Pinus albicaulis / Picea engelmannii*	8.1	2.43	1.62	0.81	**12.96**
Black oak woodland	*Quercus velutina*	11.34	0.81	0.81	0	**12.96**
Western juniper / Sagebrush savanna	*Juniperus occidentalis / Artemisia tridentata*	12.96	0.81	1.62	0.81	**16.2**
Western hemlock - Western redcedar - Douglas-fir forest	*Tsuga heterophylla / Thuja plicata / Pseudotsuga menziesii*	8.91	7.29	3.24	0.81	**20.25**
Wheatgrass - Cheatgrass grassland	*Triticum aestivum / Bromus tectorum L.*	14.58	4.86	2.43	0	**21.87**
Ponderosa pine savanna	*Pinus ponderosa*	8.1	10.53	4.05	1.62	**24.3**
Bluebunch wheatgrass - Bluegrass grassland	*Pseudoroegneria spicata / Poa* L.	14.58	7.29	4.05	0.81	**26.73**
Gambel oak / Sagebrush shrubland	*Quercus gambelii / Artemisia* L.	9.72	14.58	7.29	0	**31.59**
Scrub oak - Chaparral shrubland	*Quercus berberidifolia*	17.01	11.34	4.05	0.81	**33.21**
Pacific ponderosa pine - Douglas-fir forest	*Pinus ponderosa / Pseudotsuga menziesii*	22.68	11.34	7.29	5.67	**46.98**
Pacific ponderosa pine forest	*Pinus ponderosa*	32.4	20.25	8.1	1.62	**62.37**
Western juniper / Huckleberry oak forest	*Juniperus occidentalis / Quercus vacciniifolia*	51.03	25.11	7.29	1.62	**85.05**
Ponderosa pine - Two-needle pine - Juniper forest	*Pinus Ponderosa / Pinus* L. */ Juniperus* L.	46.98	12.96	18.63	7.29	**85.86**
Sugar pine - Douglas-fir - Ponderosa pine - Oak forest	*Pinus lambertiana / Pseudotsuga menziesii / Pinus ponderosa / Quercus* L.	54.27	32.4	19.44	6.48	**112.59**
Urban - agriculture - barren		46.98	42.12	23.49	8.1	**120.69**
Douglas-fir - ponderosa pine forest	*Pseudotsuga menziesii / Pinus Ponderosa*	63.99	31.59	23.49	9.72	**128.79**
Subalpine fir - Engelmann spruce - Douglas-fir - Lodgepole pine	*Abies lasiocarpa / Picea engelmannii / Pseudotsuga menziesii / Pinus contorta*	63.99	27.54	22.68	24.3	**138.51**
Sagebrush shrubland	*Artemisia* L.	81	42.12	15.39	1.62	**140.13**
Ponderosa pine - Jeffrey pine forest	*Pinus ponderosa / Pinus jeffreyi*	85.05	62.37	30.78	17.01	**195.21**
Interior ponderosa pine forest	*Pinus ponderosa*	96.39	49.41	32.4	21.87	**200.07**
Pinyon - Juniper forest	*Pinus edulis / Juniperus monosperma*	265.68	127.98	66.42	20.25	**480.33**
Lodgepole pine forest	*Pinus contorta*	392.85	178.2	134.46	144.18	**849.69**
	Grand Total (sq km)	**1426.41**	**735.48**	**443.07**	**277.83**	**2882.79**

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