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CHARACTERIZING BURN SEVERITY OF BEETLE-KILLED FOREST STANDS LEVERAGING GOOGLE EARTH ENGINE-DERIVED NORMALIZED BURN RATIOS

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CHARACTERIZING BURN SEVERITY OF BEETLE-KILLED FOREST STANDS LEVERAGING GOOGLE EARTH ENGINE-DERIVED NORMALIZED BURN RATIOS

By

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Characterizing burn severity of beetle-killed forests leveraging Google Earth Engine-derived normalized burn ratios

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Following numerous studies, a general consensus on burn severity in forests affected by bark beetle outbreaks has not yet been achieved. The purpose of this study is to characterize burn severities in forest stands affected by mountain pine beetle (MPB) outbreaks, especially in relation to “time since outbreak”, vegetation cover, and topographic factors. This study focuses on wildfires that occurred in the northern Rocky Mountains of Idaho and Montana during the 2012 fire season within forested areas that had previously experienced prior MPB outbreaks. Remote sensing techniques were used to quantify and compare the burn severities of MPB-outbreak stands with those of unaffected lodgepole pine; the role of fire weather was not accounted for in this study. The results indicate time since outbreak and existing vegetation cover were more important influences on burn severity when compared to topographic factors. Initial expectations were that red stage stands would exhibit the highest burn severity. These findings indicate though that 5+ year time since outbreak forest stands experienced higher burn severities compared to unaffected stands and those that were more recently affected by MPB. Increased torching potential may be attributed to increased surface fuel loads from needle fall. Statistical modeling and spatial autocorrelation were not significant but should be considered by future researchers.

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I would like to thank Jeremy Sage for his input, Philip Higuera for his expertise, and David Shively for his guidance.

I dedicate this work to my daughter, Cadence Angel, and my fiancé, JoLynn Marie.

CONTENTS

1. Introduction

As a result of climate change and long-standing forest management practices (including fire suppression and creation of even-aged stands across broad swaths of landscape), a mountain pine beetle (MPB; *Dendroctonus ponderosae*) epidemic has impacted forests of the western United States over the last 30 years (Jenkins et al. 2012; Perrakis et al. 2014; Hicke et al. 2016). In Idaho and Montana, the MPB has affected over 6.6 million hectares, mainly in high-elevation forests dominated by lodgepole pine (*Pinus contorta* Douglas ex Louden). Based on geospatial data available through the US Forest Service, large swaths of forest in Idaho and Montana contain dead-standing trees following outbreaks that occurred since the year 2000.

Forest and wildland fire managers have raised concerns over how these dead fuels will influence fire behavior and burn severity (Page et al. 2014). While research on beetle outbreak-wildfire interactions has been conducted for quite some time (e.g., Geiszler et al. 1984; Lynch et al. 2006), more recent papers have focused primarily on physical fire modeling, involving hypothetical fuel conditions and parameters (Jenkins et al. 2012; Page et al. 2014; Hoffman et al. 2015). Simulations conducted by Hoffman et al. (2012) found that sites where all susceptible trees were killed by MPB produced canopy consumption rates of 70% or more when compared to sites with no MPB-mortality.

The subsequent criticism has been that conventional fire modeling techniques have produced inaccurate results as they assume the presence of live trees, instead of dead trees (Hicke et al. 2012; Jenkins et al. 2012). Overestimates of canopy fuel consumed in simulations may likely be caused by modeling the fuels complex as a homogeneous layer (Hoffman et al. 2012). Limitations with physics-based models are likely to persist until current fire behavior models can be validated by data from accurate wildfire observations and/or experimental fires (Page et al.

2014). Although fundamentally different from fire modeling techniques, more research is emerging that incorporates post-fire data in analyses (Harvey et al. 2014a; Harvey et al. 2014b).

To date, a general consensus on how insect-affected areas alter fire behavior or burn severity has not yet been achieved, which is an observation noted repeatedly in more recent studies (Hicke et al. 2012; Hoffman et al. 2012; Black et al. 2013; McCarley et al. 2017; Meigs et al. 2016; Reiner 2017). The disparity in research outcomes may be rooted in the environmental differences caused by regional climatic conditions in addition to the varying methodologies and data sources employed by each study, in addition to limited sampling or the challenging nature of identifying proper study controls in stands that were unaffected by MPB that were similar to attacked locations (Hicke et al. 2012). The purpose of this study is to determine the effect of prior MPB outbreaks on subsequent fire severity. The study focuses on wildfires that occurred in the northern Rocky Mountains of Idaho and Montana in 2012 in areas that had experienced MPB outbreaks in the previous 12 years. The primary objective is to quantify the effects of recent MPB outbreaks on subsequent burn severity at the stand scale (i.e., 30 x 30 m), explicitly including the role of time-since-outbreak. Beetle outbreaks are classified as green/red stage (< 3 years since outbreak), grey stage (3-5 years), and old-stage trees (> 5 years). Vegetation cover (percent canopy cover) and topographic factors (slope and aspect) are also analyzed.

2. Background

Climate change and forest management practices have directly and indirectly influenced forest disturbances, such as wildfires and insect outbreaks, resulting in rapid changes to forest ecosystems in the western United States over the past several decades (Agne et al. 2016; Meigs et al. 2016; Westerling 2016). Warming temperatures have led to an increase in bark beetle-caused tree mortality over large regions, particularly in the Northern Rocky Mountains (Black et al. 2013). Mountain pine beetles have affected 6.6 million hectares of coniferous forests in 13 western states (Perrakis et al. 2014) over the past 25 years (Jenkins et al. 2012). Wildfire and bark beetle outbreaks are the two main drivers of tree mortality in the west, with insect-killed trees often surpassing annual wildfire acreage (Coleman et al. 2018), impacting more canopy area than wildfires in the western U.S. over the last thirty years (Hicke et al. 2016).

A native insect in the western U.S., the MPB has been an important disturbance agent in coniferous forest ecosystems for thousands of years. The favored host tree of the MPB is the lodgepole pine, which usually grows in dense stands that tend to have stand-replacing fire regimes (Reiner 2017). At low population levels, MPBs attack mature, old, or weakened trees, which helps create a heterogeneous forest structure by altering age-class and species composition (Agne et al. 2016). Low-level outbreaks also facilitate the recycling of nutrients and allow understory vegetation to grow by creating openings in the canopy (Jenkins et al. 2012). Increased temperatures accompanied by dry conditions in recent decades have weakened otherwise resistant trees, and have allowed for MBP populations to grow more rapidly within and between growing seasons leading to widespread outbreaks that dramatically alter stand structure, composition, and fuels quantity (Jenkins et al. 2012; McCarley et al. 2017).

Although the spatial and temporal overlap of beetle activity and wildfire are relatively infrequent, anecdotal evidence has shown that fire behavior has not followed modeled fire predictions when beetle outbreaks precede the occurrence of wildfire (Page et al. 2013). Oral accounts from fire fighters and fire specialists note unusual and extreme fire behavior within MPB-affected stands, such as canopy fuels igniting in the absence of surface fire, or low intensity surface fires that have initiated crown fires (Page et al. 2013). Both types of fire behavior contribute to rapid fire spread (Perrakis et al. 2014; Reiner 2017). Fire crews have also reported heavy dead surface fuel build-up, prolific spotting, and trees that are more prone to uprooting or mid-tree breakage during fires than dead trees killed by other causal agents (Jenkins et al. 2012). Gaining a better understanding of how these linked disturbances behave is paramount to fire fighter safety and fire suppression management strategies (Page et al. 2013).

Due to the spatial and temporal variability of bark beetle outbreaks, affected stands produce heterogeneous forest structure that contain trees in various stages of mortality, described by 'time since outbreak.' The needles of MPB-killed trees transition from green to red-stage within one year as photosynthetic activity ceases, gradually dropping their needles during the grey-stage between 3 to 5 years; trees are largely denuded of needles once reaching the old-stage beyond the fifth year (Perrakis et al. 2014). The time since outbreak impacts foliar moisture content, which is greatly diminished over time (Hicke et al. 2012). For example, foliar moisture content for lodgepole pine was approximately 109% in live trees compared to 12% for red-stage trees in Montana (Reiner 2017). This lowers the temperature threshold necessary for a surface fire to initiate crown fires and promotes spotting over greater distances (Jenkins et al. 2012; ; Reiner 2017).

The literature contains very few case studies of how bark beetle outbreaks have influenced subsequent fire behavior (Meigs et al. 2012; Harvey et al. 2014*a*; Harvey et al. 2014b; Agne et al. 2016)), and currently there is no general consensus on this particular disturbance interaction – a fact that has been noted in several past reviews (Hicke et al. 2012; McCarley et al. 2017; Reiner 2017). This is likely due to the variety of methodologies employed to analyze the effects of MPB on wildfire severity, or the inadequacies of the models used. Fuels were typically addressed by observational studies, while fire behavior was typically addressed by modeling studies (Hicke et al. 2012). Some simulations assume homogenous stands of live trees rather than capturing the variability of foliar moisture and canopy bulk density found in stands of beetle-killed trees (Hoffman et al. 2012; Jenkins et al. 2012; Perrakis et al. 2014). A key metric of fire effects is burn severity, which is the qualitative measure of fire impacts on soils and above ground biomass. In subalpine forests, fire severity is typically directly related to fire intensity during a fire event, such that areas with high burn severity presented hazardous conditions for fire fighters during the event (Jenkins et al. 2012). Fire severity also dictates, in part, how a forest ecosystem recovers after a fire event (Keely 2009).

2.1 Foliar Flammability and Chemistry

Following a MPB attack, the foliage of the host lodgepole pine undergoes dramatic changes in moisture content and chemical composition as the tree transitions from initial decline to death. In the early green-attack/yellow stage (< 1 year since attack), crown fire potential increases as the desiccated needles are still retained in the tree canopy, persisting through the red-stage (< 3 years since attack (Page et al. 2012). Dead and dying lodgepole pine foliage contains considerable amounts of volatile terpenes compared to live foliage, with attacked trees showing higher terpene emission rates within the first year, increasing flammability potential (Page et al. 2012). As foliar moisture content continues to decrease following tree death, crown flammability increases. This increase in crown flammability remains high for another 2-3 years, the length of time it takes for the needles to fall from the tree (Jolly et al. 2012).

Foliage samples collected from beetle-attack and non-attack lodgepole pine revealed that time-to-ignition was strongly influenced by time since beetle attack. When compared to non-attack green foliage, yellow and red foliage showed shorter ignition times, reduced ignition temperatures, and higher heat yields (Page et al. 2012). Burn tests conducted in a controlled laboratory environment showed that red needles ignited in an average of 13 seconds, compared to an average of 35 seconds for green needles. A model combining foliar moisture content, crude fat, and fiber explained 92% of the variation in time until ignition (Jolly et al. 2012). These results suggest beetle-attacked trees that still have most of their needles in the canopy may be at greater risk of crown fire initiation, as less heat energy is necessary to ignite canopy foliage.

2.2 Modeled and Simulated Fire Behavior

A number of improved simulation and modeling techniques have been developed that incorporate physics-based coupled fire/atmosphere interactions, in addition to accounting for heterogeneous fuel structure that results from variable MBP outbreak severity (i.e. percentage of trees killed). These simulation models found that in forest stands with dead canopy foliage, representing MPB-caused morality, canopy fuel consumption, crown fire intensity, and rate of spread all increased when compared to unaffected lodgepole pine stands (Hoffman et al. 2012; Perrakis et al. 2014). Results also suggest that pre-attack forest structure and outbreak severity influence crown fire behavior through the red-stage, where trees still retain dead needles and canopy bulk density remains largely unchanged.

A strong linear relationship has been observed between modeled MPB outbreak severity, predicted canopy fuel consumption, and crown fire intensity; outbreak severity explained 67% of the variability in modeled canopy fuel consumption and 50% of the modeled crown fire intensity (Hoffman et al. 2012). Under moderate burning conditions, simulations predicted that fires would have spreading rates of 2.7 times higher on average during the first five years following MPB attack when compared to unaffected lodgepole pine stands (Perrakis et al. 2014). Surface fire rate of spread was also influenced by declines in canopy bulk density from needle fall, which increased surface wind speeds. As crown foliage is reduced, it lowers the source of drag on wind, which can produce channelized wind flow when there is continuity in beetle outbreak (Hoffman et al. 2015).

2.3 Empirical Observations

One of the first studies to collect extensive field data on beetle-wildfire interaction evaluated several wildfires that occurred in 2011 throughout the Northern Rocky Mountain states of Idaho and Montana (Harvey et al. 2014*b*). Its findings included results that differed from predictions based on simulation models and fine-scale fire behavior observations and suggested that recent pre-fire MPB outbreak severity had very little impact on fire severity, as the primary drivers were extreme burning conditions and topography. Fire severity was largely unaffected under moderate burning conditions for both red stage (outbreak < 3 years before fire) and grey stage (outbreaks 3-10 years before fire). Under extreme burning conditions, red stage had few effects detected, while grey stage showed increases related to surface fire severity.

Another beetle-wildfire study conducted by the same lead author examined wildfires that occurred in the Greater Yellowstone Ecosystem in 2008 and 2011 (Harvey et al. 2014*a*). This study found that pre-fire beetle outbreak severity was moderately linked to fire severity, with changes in strength and direction influenced by time since outbreak and burning conditions. Under moderate burning conditions, green-attack/red stage (0-2 years following beetle outbreak) showed that several fire severity measures increased with pre-fire MPB outbreak severity, while fire severity decreased with outbreak severity in the grey stage (3-15 years following beetle outbreak). During extreme burning conditions, the higher levels of pre-fire MPB outbreak severities were weakly associated for both red and grey stage. The Greater Yellowstone

Ecosystem beetle-wildfire interactions demonstrated that green-attack/red-stage canopy fire severity increased under moderate burning conditions, which were consistent with fuel property and fire simulation modeling.

3. Methods

3.1 Objectives

The purpose of this study is to characterize the burn severity of MPB-killed stands, based on the concept of "time since outbreak", to determine the effect of such fuels on burn severity; Hicke et al. (2012) found that time since outbreak was one of the factors that clearly caused variability in responses. The unit of analysis is of the 30 x 30 m pixel. This variable will be combined with Existing Vegetation Cover (EVC) and the Slope-Cosine-Aspect Index (SCAI) to determine the relative influence of each in relation to burn severity. Birch et al. (2015) found that "bottom-up" inputs, such as vegetation and topography, have a greater influence on predicting burn severity than climate and weather; this finding was the reasoning for excluding fire weather as a variable for this study. The most important variable predicting burn severity was EVC, with the Slope-Cosine-Aspect Index (SCAI) coming in a distant second (Birch et al. 2015). This study examined 34 wildfire events that occurred in the Northern Rocky Mountains in Idaho and Montana during the 2012 fire season, within burned forested areas that had experienced a prior MPB-outbreak event (Figure 1).

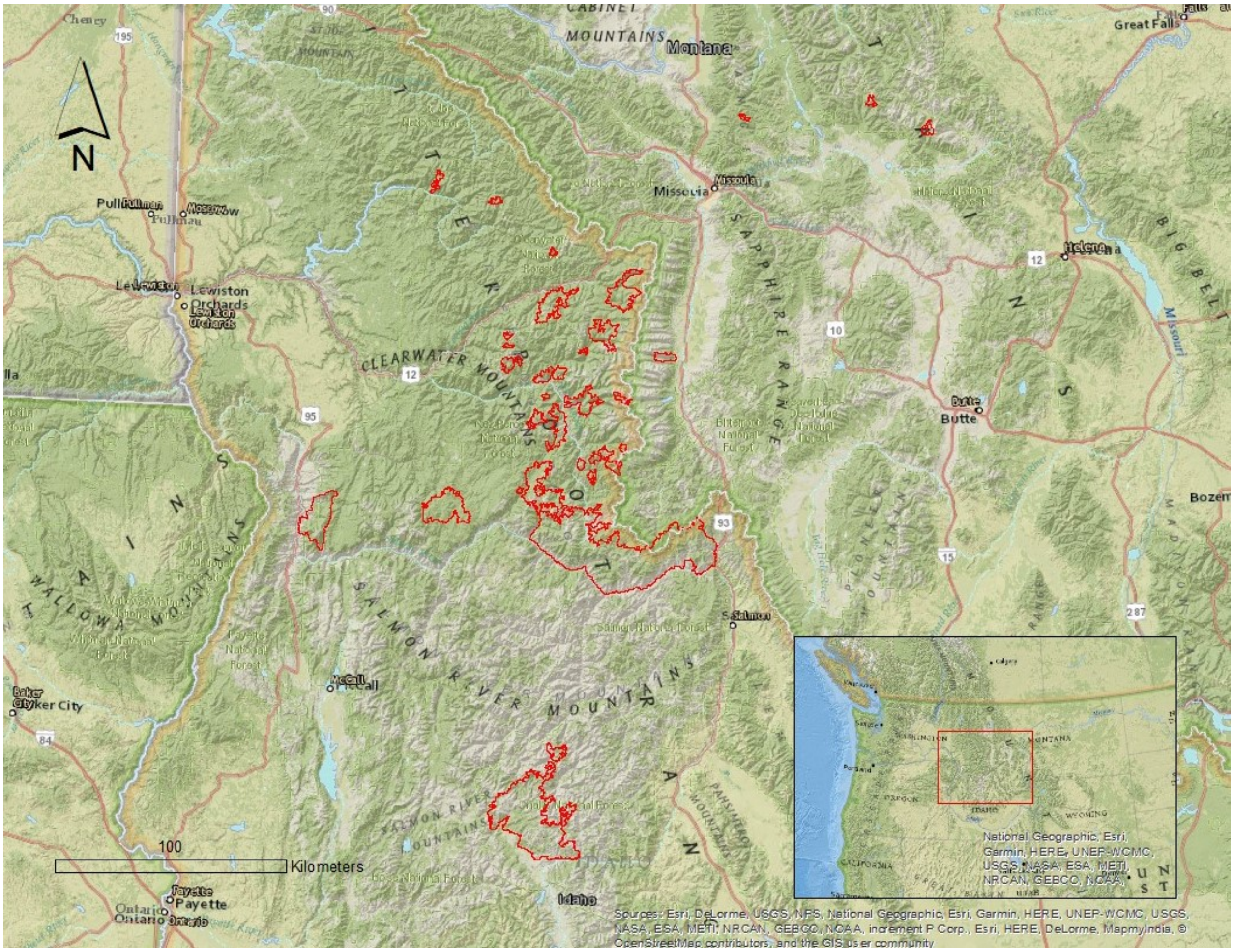


Figure 1. Study area of central Idaho and western Montana showing the 34 fires from 2012.

The primary objective is to quantify the stand-scale (i.e., 30 x 30m) effects of recent MPB outbreaks on subsequent burn severity, with explicit attention to the role of time since outbreak. Beetle outbreaks were classified as green/red stage (< 3 years since outbreak), grey stage (3-5 years), and old-stage trees (> 5 years). Vegetation cover (percent cover) and topographic factors (slope and aspect) are also analyzed.

3.2 Data Sources

3.2.1 Monitoring Trends in Burn Severity Program

The Monitoring Trends in Burn Severity (MTBS) program maps the fire severity and perimeters of large wildland fires in the United States dating back to 1984. The MTBS program was initiated in 2006 by the Wildland Fire Leadership Council (WFLC), an interagency body with responsibility for implementing the National Fire Plan (https://www.forestsandrangelands.gov/resources/overview/), and it is jointly managed by the U.S. Geological Survey's (USGS) Center for Earth Resources Observation and Science (EROS) and the U.S. Department of Agriculture Forest Service's Remote Sensing Applications Center (RSAC). The USGS National Satellite Land Remote Sensing Data Archive is the primary repository for MTBS image data, which can be downloaded for free using the USGS Global Visualization Viewer (GloVis; http://glovis.usgs.gov/), developed by USGS EROS (Eidenshink et al. 2007).

The MTBS program's primary objective is to provide burn severity information necessary to analyze trends in national fire severity for the National Fire Plan over time. Secondary objectives include providing regional and sub-regional geospatial and fire-specific data to support resource management, monitoring, and research activities. The MTBS program divides the United States into regional zones that represent similar ecological conditions, mapping fires greater than 202 hectares (500 acres) in the East, and 404 hectares (1,000 acres) in the West. As defined by the MTBS program, burn severity is the "degree to which a site has been altered or disrupted by fire; loosely, a product of fire intensity and residence time" (Eidenshink et al. 2007, 5), is a 'map-able' product using remotely sensed imagery, and relates primarily to fire-effects on the vegetative biomass in the upper strata. Historical burn severity data have allowed agencies and scientists to understand the immediate and long-term post-fire effects over a broad range of spatiotemporal scales in addition to interpreting the mosaic effects that occur within individual fire perimeters (Eidenshink et al. 2007).

The remotely sensed satellite imagery used for MTBS are from the Landsat library processed by the National Land Archive Production System (NLAPS; http://eros.usgs.gov/guides/images/landsat_tm/nlapsgeo2.html) at USGS EROS. The spectral response of individual fires is based on imagery collected by the Thematic Mapper (TM, Landsat 4-5), Enhanced Thematic Mapper Plus (ETM+, Landsat 7), and Operational Land Imager (OLI, Landsat 8) spaceborne sensors. The principal geospatial output layers produced include the pre- and post-fire Normalized Burn Ratio (NBR), differenced NBR (dNBR), thematic burn severity classification, and dNBR-derived fire perimeters (Eidenshink et al. 2007).

The USGS and Forest Service have used the NBR in fire severity mapping efforts since 2002, which has proven to be relatively accurate and cost effective (Eidenshink et al. 2007). Pre- and post-fire scene pairs are selected for each fire as close to peak gross primary production (GPP), or ‘peak of green’ conditions, that are as close to cloud-free as obtainable. Depending on the location’s latitude, this is generally between the months of April-July. The pre-fire image would be preferentially selected from the ‘peak of green’ period that same year the fire occurred. A suitable pre-fire substitute image would be from the year prior. The post-fire image should be selected from the growing season immediately following the fire, which is normally ‘peak of green’ the subsequent year. This extended assessment is ideal for forest and shrub ecosystems as it captures lagging first-order fire effects, such as delayed tree mortality, and ecologically significant second-order effects, such as initial post-fire vegetative response (Eidenshink et al. 2007).

The NBR is calculated as follows:

$$\text{NBR} = \left(\frac{NIR - SWIR2}{NIR + SWIR2}\right)$$

where NIR is the near-infrared band (TM and ETM+, band 4; OLI, band 5) and SWIR2 is the shortwave infrared 2 band (all sensors, band 7). The NIR band is sensitive to chlorophyll content, which is highly reflective in live, healthy vegetation. The SWIR2 band is sensitive to water content, which is absorbed in vegetation with high moisture content (Miller and Thode 2007). The post-fire NBR image is subtracted from the pre-fire NBR to generate the differenced Normalized Burn Ratio (dNBR), which MTBS analysts will use to digitize fire perimeters (Eidenshink et al. 2007). A "relativized" dNBR (RdNBR) is also processed, which accounts for variable spectral signatures for high severity fires due to differences in pre-fire tree canopy density (Miller and Thode 2007).

The RdNBR is a thematic raster dataset with integer values associated with each 30 m pixel (Eidenshink et al. 2007). Positive values generally represent a negative change in greenness (mortality), while negative values generally indicate positive vegetative response (regrowth). Burn severity is then partitioned into seven discrete classes:

Enhanced Regrowth, High (-550 to -251)
Enhanced Regrowth, Low (-250 to -101)
Unburned (-100 to 99)
Low Severity (100 to 269)
Moderate-low Severity (270 to 439)
Moderate-high Severity (440 to 659)
High Severity (660 to 1350)

3.2.2 Google Earth Engine (GEE) Data

A recent study leveraging the computational power of Google Earth Engine (GEE) produced burn severity classifications that were generally more accurate than those produced by the MTBS process (Parks et al. 2018). A cloud-based platform capable of planetary-scale geospatial analysis (Robinson et al. 2017), GEE maintains a multi-petabyte public catalog of commonly used remote sensing datasets, including the entire Landsat archive (Gorelick et al. 2017). Rather than having to manually select individual pre- and post-fire imagery, which can be a very time-consuming process, the GEE procedure utilizes a mean compositing approach over a pre-specified date range (pre- and post-fire). All valid, cloud-free pixels are stacked, with the mean value of each pixel used to calculate the resulting burn severity layers. The process only requires a GIS-input shapefile containing polygons that delineate fire perimeters, which are freely available from the MTBS website for download.

Similar to the MTBS data, the GEE process creates NBR and dNBR layers. However, an additional "offset" processing step is introduced before creating the RdNBR. The average values of all unburned pixels 180 m outside of the fire perimeter are calculated to produce a $\text{dNBR}_{\text{offset}}$ layer. This intermediate step accounts for the differences in pixel value that is introduced due to variable phenology or precipitation between pre- and post-fire imagery. The GEE-based burn severity products generally achieve higher overall accuracy and correspondence to field data, and the RdNBR created from the "offset" approach yields even higher accuracies, especially when comparing multiple fires with different ignition dates (Parks et al. 2018). A link to the GEE code to implement these methods is provided by Parks et al. (2018).

3.2.3 Aerial Detection Survey (ADS)

Insects and diseases have caused millions of hectares of defoliation and tree mortality in the U.S. annually. As directed by Congress, the USDA Forest Service's Forest Health Protection (FHP) program conducts annual aerial detection surveys (ADS) to report forest conditions by mapping tree injury and mortality from insects, disease, or abiotic causes (Coleman et al. 2018). The ADS is one step in a multi-tiered approach to detect, evaluate, and monitor significant events or changes occurring in forested landscapes. Additional remote sensing and ground surveying techniques are also applied to complement the ADS, all of which are subjected to some degree of ground-truthing (Johnson and Wittwer 2008).

Aerial surveying, or sketch-mapping, is a remote sensing technique to manually document forest change onto a map, and is primarily conducted during the summer months. The surveys are performed from high-winged aircraft capable of flying at relatively slow speeds (approximately 100 knots or 115 mph). Traditionally, a trained observer records affected areas onto a paper 1:24,000 scale USGS topographic base-map, delineating their sizes, shapes, and locations as accurately as possible. Attributes recorded include host (i.e., tree species), causal agent (insect species), symptom, outbreak severity, and percentage or number of trees affected. Practiced in the United States since the 1950s, aerial surveys have proven to be an efficient and cost-effective method to map and monitor disturbance agents over large forested areas (Johnson and Wittwer 2008).

In recent years, the Forest Service's Forest Health Technology Enterprise Team has designed and implemented a Digital Aerial Sketch Mapping (DASM) system that uses Global Positioning System (GPS)-enabled, touch-screen tablets. These novel technologies allow the observer to quickly digitize polygons directly into the mapping software, which can later be downloaded and processed to create Geographic Information System (GIS) shapefile layer. The DASM system has also eliminated the need to hand-digitize the paper maps, a time-consuming post-processing phase necessary in order to create GIS datasets (Johnson and Wittwer 2008).

Since the collection of ADS data is highly subjective, dependent upon the training and experience of the observer, the resulting data products are also highly subjective and variable. On average, an airborne observer has approximately 30 seconds per mile to recognize, classify, and record all of the disturbance activity they see in a swath about 1.5 miles wide (Johnson and Wittwer 2008). Ground-truthing of ADS data does occur, but due to time and budgetary constraints it is typically conducted on < 1% of data surveyed annually (Coleman et al. 2018). These factors introduce a number of limitations and possible errors associated with the ADS program. These include, but are not limited to the correct spatial location and extent of damage, or the accurate identification of existing damage. The ADS data have been recognized as reasonable input for coarse spatial-scale analysis (Egan 2014), best-suited for identifying trends rather than precise measurements (Johnson and Wittwer 2008). However, the data have also been used at finer-scales by many agencies, researchers, and land managers (Coleman et al. 2018).

Recently, a study assessing ADS data collected between 2012 and 2014 found that the overall accuracy was > 70% when compared to ground-collected data (Coleman et al. 2018). Accurately identifying the biotic agent was highly dependent upon correctly identifying the tree species, which affected the accuracy of the polygon boundaries. This accuracy assessment encompassed all insect and pathogen types, of which phloem feeders (bark beetles) represented 55% of all casual agents. Damage recorded as tree mortality, with the dominant damage-type (55%) largely attributed to bark beetles, achieved commission errors of only 2%. High overall accuracies were achieved for recording damage type (97%), genera/forest cover type (96%), tree species (87%), and feeding guild or injury category (84%).

While accuracy decreased when identifying damage agent species (70%), mountain pine beetle achieved low levels of commission error (10%). Since many insects and diseases are host-specific, correct identification of the damaging agent is highly dependent upon the accuracy of observing the correct tree species. Thus, high levels of accuracy for MPB observations in the Rocky Mountain region is attributed to their host-specific preference of lodgepole pine, which also had high accuracy rates of identification. Introduction of the GPS-capable DASM system may be a contributing factor to high accuracies as it has enabled observers to spend more time mapping tree injury and mortality, rather than continually geo-referencing their location before recording their observations (Coleman et al. 2018).

3.2.4 LANDFIRE Program

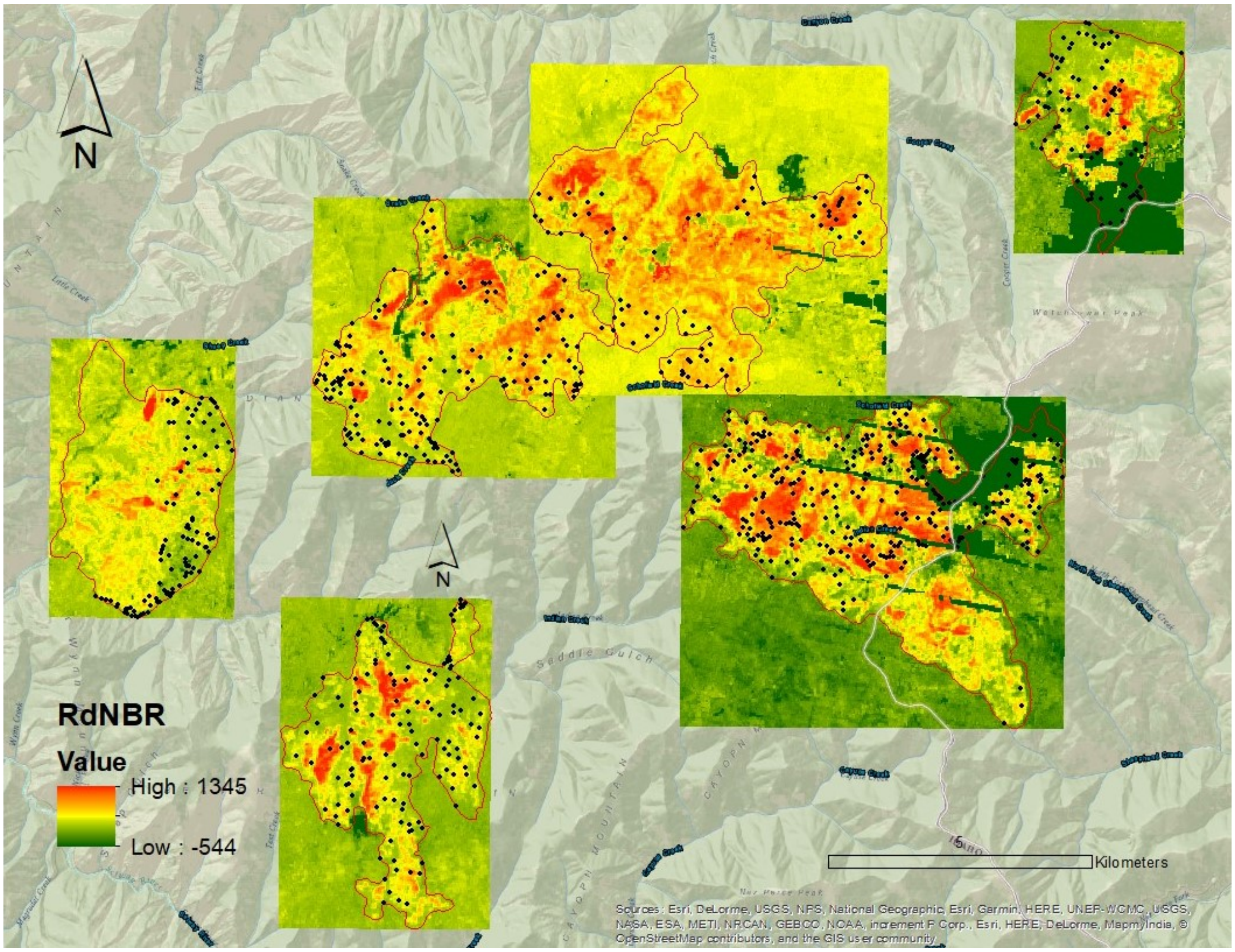
Launched in 2004 by the Wildland Fire Leadership Council, the LANDFIRE program is a multi-agency initiative that produces consistent and comprehensive geospatial data products. Using an interdisciplinary, science-based approach, these 30-m resolution raster grid maps and data describe vegetation and wildland fuels across the United States, in addition to fire regimes and ecological departure from historical conditions. Jointly operated by the USDA Forest Service and USGS EROS, its purpose is to facilitate national and regional-level wildfire management planning and reporting. In particular, LANDFIRE supports the development of wildland fire suppression strategies, community and firefighter protection, and effectively allocating wildfire resources (Rollins 2009).

3.3. Analytical Methods

Thirty-four fires from 2012 in northern Idaho and western Montana were examined using Environmental Systems Research Institute's ArcGIS 10. The total areal extent of these fires covered 373,707 hectares (923,450 acres). Fire perimeter polygons from the MTBS program were used as inputs to create GEE-derived burn severity layers, with RdNBR as the final product. The ADS dataset was utilized to locate beetle outbreak areas, and these were merged and categorized as green/red stage (< 3 years since outbreak, 2010-2012), grey stage (3-5 years, 2007-2009), and old-stage trees (> 5 years, 2000-2006). Only pixels with beetle-killed trees located within the burn perimeters were considered. Available ADS data for the study area dated back to 2000, and did not contain information related to outbreak severity.

The LANDFIRE 2010 version provided Existing Vegetation Type (EVT), Existing Vegetation Cover (EVC), Vegetation Disturbance (VDIST), slope, and aspect datasets. The EVT dataset was used as a base-layer to identify vegetation assemblages that contained lodgepole pine. This layer was then applied as a mask to the ADS data so that only pixels identified as having lodgepole pine were included in the analysis. This same mask was applied to the EVC layer, which provided cover-percentage data as a proxy for available surface fuels. The VDIST fire history data only went back to 1984, so this was supplemented with the fire history data available from the U.S. Forest Service Region 1, which dates back to the late-1800s. All areas that experienced fire within the last 79 years were excluded from analysis, as it takes approximately 80 years for lodgepole pines to reach the 20 cm (~8 in) diameter at breast height (1.4 m above the ground) that MPB prefer (Negron 2019). Non-vegetated areas, such as natural barren, water, and man-made features, were also excluded. Slope and aspect data were used to calculate the Slope-Cosine-Aspect Index. Higher values produced by this index indicate steeper slopes and/or more northern-facing aspects, and it also likely approximates the effective moisture of fuels available to burn (Birch et al. 2015).

Following Birch et al. 2015, random sampling points were generated for the entire study area using the 34 fire perimeters as boundaries without stratification, with 127.5 m established as the minimum distance in between points (Figure 2.). This distance prevents adjacent pixels from being selected, minimizing spectral mixing (or the adjacency affect, which can confound results) (Birch et al. 2015), and spatial autocorrelation. These points were used to extract data from the RdNBR, ADS, EVC, and Slope-Cosine-Aspect Index layers. Any pixels that had RdNBR < -550 or > 1350 were removed, in addition pixels with EVC values of 0%. This left 49,385 sample pixels, or the equivalent of 4,445 hectares (10,984 acres).



Sources: Esri, DeLorme, USGS, NPS, National Geographic, Esri, Garmin, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp., Esri, HERE, DeLorme, MapmyIndia, © OpenStreetMap contributors, and the GIS user community

Figure 2. Example of Google Earth Engine derived RdNBR layers and randomly sampled points in the Selway-Bitterroot Wilderness.

4. Results

The RdNBR values extracted from the 49,385 randomly sampled pixels ranged from -544 to 1,345, with an overall mean value of 307 (Table 1, Figure 3). The mean RdNBR values were 291 for pixels unaffected by MPB, 320 for green/red stage, 321 for grey-stage, and 361 for old-stage. All of these mean values fall within the range of moderate-low severity (270 to 439) on the RdNBR Burn Severity scale. When comparing the mean RdNBR values for each burn severity class and tree-type (e.g., low severity; grey = 186) to the total burn severity class RdNBR mean (low severity; total = 184), all categories that had at least 31 extracted pixels that were +/- 9 of the total mean. There was only one category (green/red, enhanced regrowth, high) that fell outside of this (-73), but it had only five extracted pixels. Pixels unaffected by MPB were mainly classified in the unburned (24.8%), low (24.2%), and moderate-low (19.0%) burn severity categories, accounting for 57.0% of the burn severity for this lodgepole pine forest-type. Burn severity of green/red stage, grey-stage, and old-stage pixels were primarily classified as low (28.8%, 23.2%, and 22.7% respectively), moderate-low (21.6%, 21.6%, 20.4% respectively) and moderate-high (21.9%, 20.9%, and 20.6% respectively). As a whole, the low severity category contained the highest percentage of pixels (24.0%), followed by unburned (22.1%), moderate-low (19.7%), and moderate-high (19.0%) severity. For pixels that fell within the high severity range, this accounted for 10.6% of unaffected pixels, 9.6% for green/red stage, 11.9% of grey-stage, and 17.5% of old-stage. If MPB-caused mortality significantly affected burn severity, then one would expect that a greater proportion of pixels to burn at higher severity would be found during the earliest, green/red stage of beetle-kill, and gradually decline in severity as these trees transition to grey-stage, and then finally to old-stage. However, these results indicate that the opposite occurred.

Table 1. RdNBR burn severity classes.

	unaffected by MPB			**green/red**			**grey**			**old**			**total**		
RdNBR Burn Severity Classes	**mean RdNBR**	**# of pts**	**%**	**mean RdNBR**	**# of pts**	**%**	**mean RdNBR**	**# of pts**	**%**	**mean RdNBR**	**# of pts**	**%**	**mean RdNBR**	**# of pts**	**%**
Enhanced Regrowth, High (-550 to -251)	-352	237	0.7%	-429	5	0.2%	-354	63	0.8%	-365	79	1.1%	*-356*	*384*	*0.8%*
Enhanced Regrowth, Low (-250 to -101)	-151	848	2.6%	-144	31	1.5%	-149	187	2.4%	-159	196	2.8%	*-152*	*1262*	*2.6%*
Unburned (-100 to 99)	16	8038	24.8%	19	341	16.4%	12	1506	19.2%	13	1053	14.9%	*15*	*10938*	*22.1%*
Low Severity (100 to 269)	183	7847	24.2%	185	600	28.8%	186	1813	23.2%	184	1603	22.7%	*184*	*11863*	*24.0%*
Moderate-low Severity (270 to 439)	351	6150	19.0%	350	450	21.6%	352	1693	21.6%	352	1440	20.4%	*351*	*9733*	*19.7%*
Moderate-high Severity (440 to 659)	542	5865	18.1%	547	455	21.9%	542	1632	20.9%	543	1451	20.6%	*542*	*9403*	*19.0%*
High Severity (660 to 1350)	795	3434	10.6%	746	200	9.6%	783	930	11.9%	809	1238	17.5%	*794*	*5802*	*11.7%*
	291	**32419**	**100.0%**	**320**	**2082**	**100.0%**	**321**	**7824**	**100.0%**	**361**	**7060**	**100.0%**	***307***	***49385***	***100.0%***

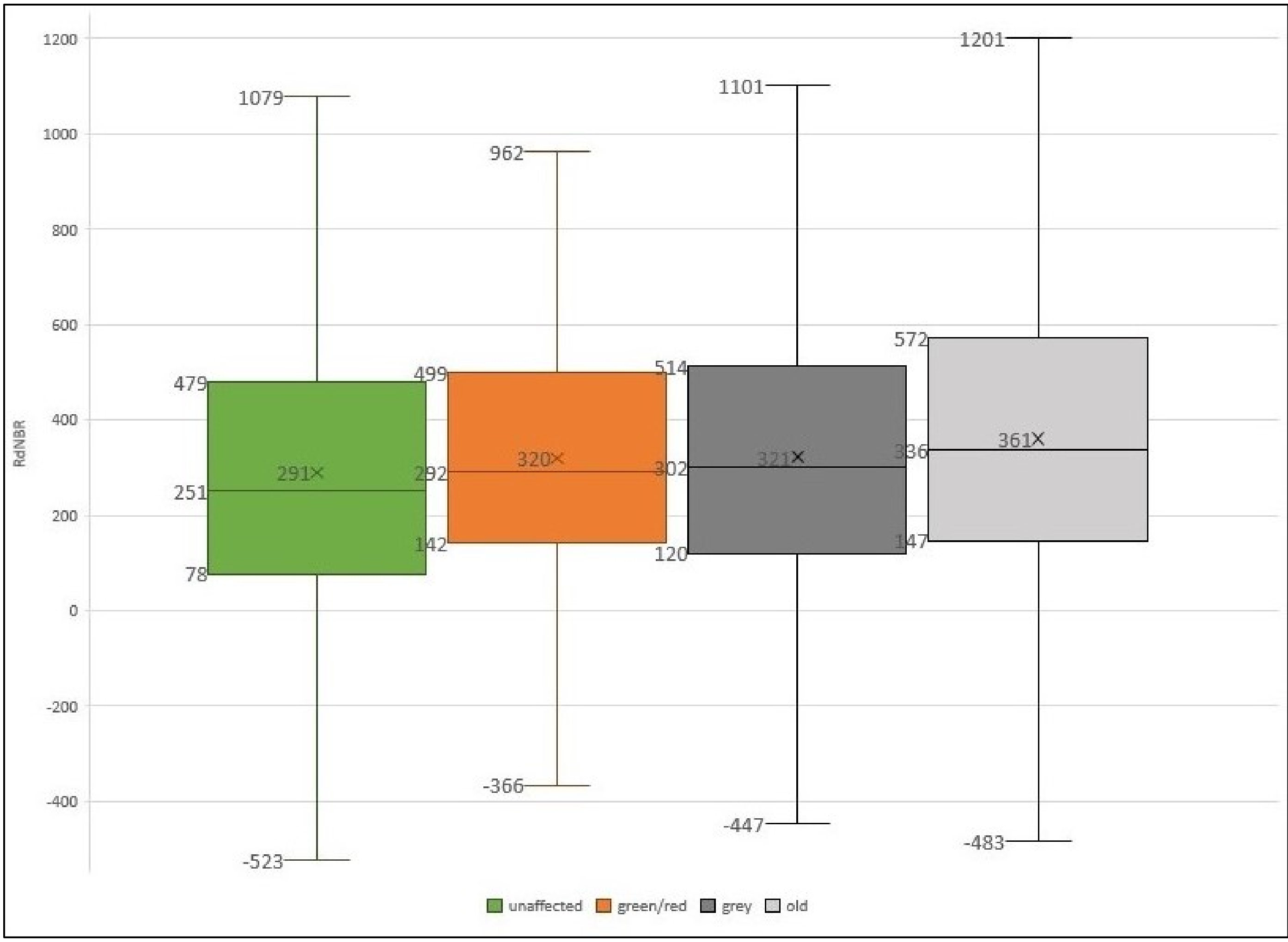


Figure 3. RdNBR of unaffected and MPB-killed time since outbreak classes. Note: Boxplot values shown (top-to-bottom are maximum, 75th percentile, median, mean (numeric value is written in front of symbol "X"), 25th percentile, and minimum. RdNBR values: Enhanced Regrowth, High (-550 to -251), Enhanced Regrowth, Low (-250 to -101), Unburned (-100 to 99), Low Severity (100 to 269), Moderate-low Severity (270 to 439), Moderate-high Severity (440 to 659), High Severity (660 to 1350).

The majority of the existing vegetation cover burned at moderate-low severity, ranging from RdNBR values of 270 to 439 (Table 2, Figure 4). The 30% EVC class contained the highest proportion of pixels (29.0%), with all four tree-types having the highest percentage EVC in this category. This was followed by 40% EVC (21.6%), and 20% EVC (20.5%), accounting for 71.1% of all EVC percentages. All tree-types had their lowest RdNBR values in the 10% and 20% EVC categories, with an overall average of -64 (unburned) and 117 (low severity), respectively. While covering a smaller areal extent (2.4%), 90% EVC displayed the highest RdNBR (1335), followed by 80% EVC (989), and 70% EVC (764). All three of these RdNBR values fell within the high severity (660 to 1350) range. The 30% EVC, and 60-80% EVC categories displayed an increasing RdNBR trend when progressing from unaffected, green/red, grey, to old-stage pixels, with old-stage pixels demonstrating the highest RdNBR values for all four of these EVC% categories.

Table 2. Existing Vegetation Cover

	unaffected by MPB			**green/red**			**grey**			**old**			**total**		
EVC %	**mean RdNBR**	**# of pts**	**%**	**mean RdNBR**	**# of pts**	**%**	**mean RdNBR**	**# of pts**	**%**	**mean RdNBR**	**# of pts**	**%**	**mean RdNBR**	**# of pts**	**%**
10%-20%	-85	3694	11.4%	0	142	6.8%	0	627	8.0%	4	450	6.4%	*-64*	*4913*	*9.9%*
20%-30%	84	6934	21.4%	160	339	16.3%	177	1332	17.0%	207	1496	21.2%	*117*	*10101*	*20.5%*
30%-40%	336	8855	27.3%	474	624	30.0%	521	2096	26.8%	615	2756	39.0%	*423*	*14331*	*29.0%*
40%-50%	496	6214	19.2%	49	544	26.1%	183	2057	26.3%	369	1837	26.0%	*391*	*10652*	*21.6%*
50%-60%	430	3347	10.3%	72	259	12.4%	153	1114	14.2%	233	435	6.2%	*335*	*5155*	*10.4%*
60%-70%	391	2271	7.0%	554	149	7.2%	610	555	7.1%	660	50	0.7%	*444*	*3025*	*6.1%*
70%-80%	752	868	2.7%	866	21	1.0%	873	39	0.5%	885	30	0.4%	*764*	*958*	*1.9%*
80%-90%	974	228	0.7%	1187	4	0.2%	1236	4	0.1%	1265	6	0.1%	*989*	*242*	*0.5%*
90%-100%	1335	8	0.0%			0.0%			0.0%			0.0%	*1335*	*8*	*0.0%*
	291	**32419**	**100.0%**	**320**	**2082**	**100.0%**	**321**	**7824**	**100.0%**	**361**	**7060**	**100.0%**	***307***	***49385***	***100.0%***

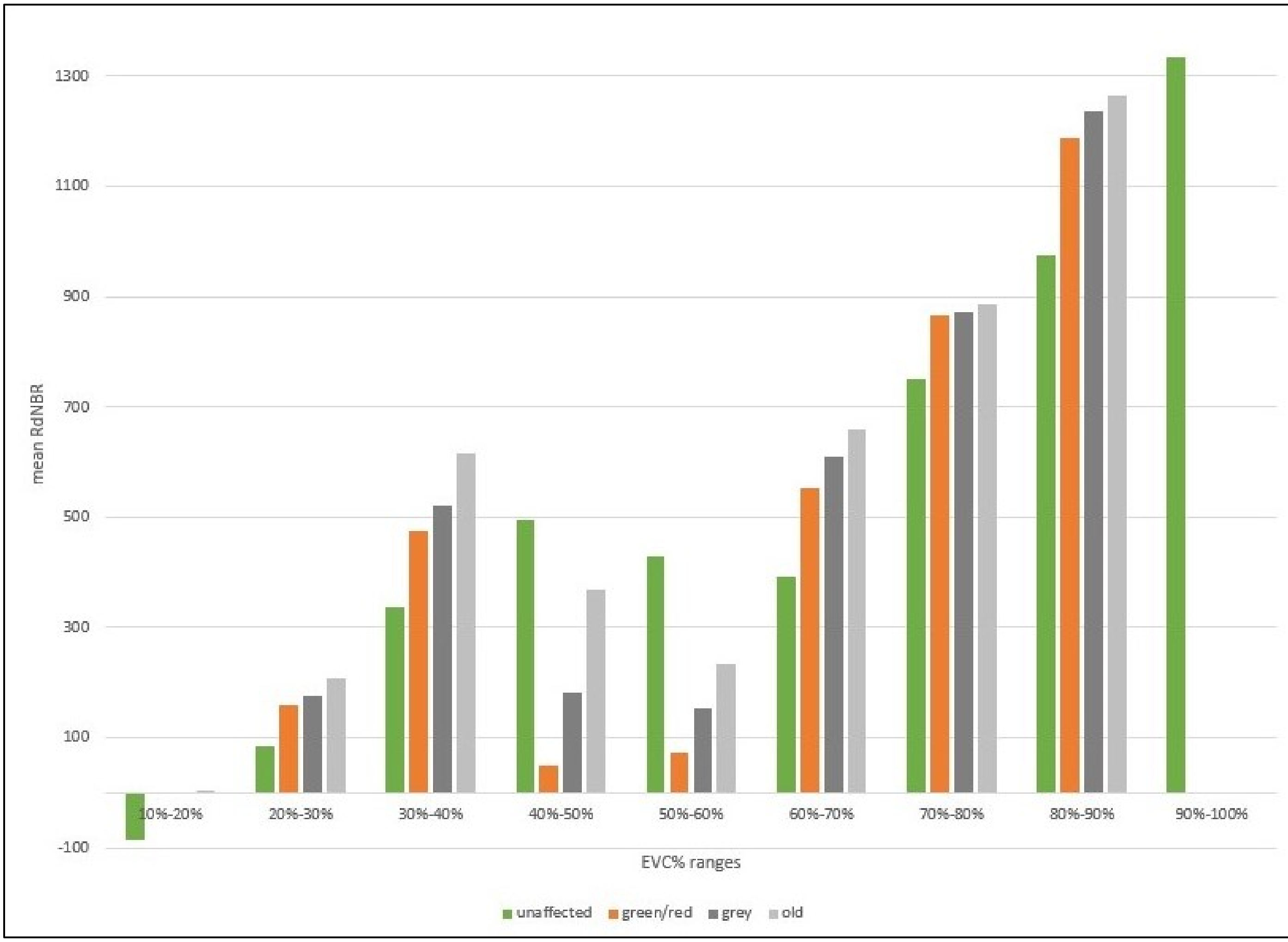


Figure 4. Mean RdNBR values for each existing vegetation cover class (EVC, %). RdNBR values: Enhanced Regrowth, High (-550 to -251), Enhanced Regrowth, Low (-250 to -101), Unburned (-100 to 99, Low Severity (100 to 269), Moderate-low Severity (270 to 439), Moderate-high Severity (440 to 659), High Severity (660 to 1350).

In examining the Slope-Cosine-Aspect Index (SCAI), the majority of the sampled pixels were located on shallow-sloped northern (27.7%; SCAI 0 to 15.0) and southern (27.1%; SCAI -15.0 to -0.1) aspects, which had average RdNBR values of 394 (moderate-low severity) and 173 (low severity), respectively (Table 3, Figure 5). Overall, the RdNBR values increased the steepest southern facing slopes, transitioning to shallow south and north-facing slopes, and then to the steep northern slopes, which displayed the highest RdNBR figures. Southern facing slopes, those with negative SCAI values, all had lower RdNBR values when compared to those with positive SCAI values on the north-facing slopes. The steepest south-facing slopes with negative SCAI values of -60 to -45.1 showed RdNBR values of enhanced regrowth, high (-550 to -251), with a mean of RdNBR -521. All tree-types within this index range reflected this, with the exception of old-stage pixels, which had a value of 0, indicative of unburned conditions (-100 to 99). The remaining three south-facing slopes made up 49.3% of all pixels, showing RdNBR values of: 1) -170 (SCAI -45.0 to -30.1; enhanced regrowth, low), 2) 3 (SCAI = -30.0 to -15.1; unburned), and 173 (SCAI -15.0 to -0.1; low severity). Accounting for approximately 22.8% of the pixels examined, the three steepest north-facing slope indices had RdNBR values of 638 (SCAI 15.1 to 30.0; moderate-high severity), 902 (SCAI 30.1 to 45.0; high severity), and 1,306 (SCAI 45.1 to 60.0; high severity).

Table 3. Slope-Cosine-Aspect Index

	unaffected by MPB			**green/red**			**grey**			**old**			**total**		
SCAI	**mean RdNBR**	**# of pts**	**%**	**mean RdNBR**	**# of pts**	**%**	**mean RdNBR**	**# of pts**	**%**	**mean RdNBR**	**# of pts**	**%**	**mean RdNBR**	**# of pts**	**%**
-60 - -45.1	-519	23	0.1%	-545	1	0.0%	-546	1	0.0%	0	0	0.0%	*-521*	*25*	*0.1%*
-45.0 - -30.1	-156	1536	4.7%	-135	58	2.8%	-228	188	2.4%	-416	50	0.7%	*-170*	*1832*	*3.7%*
-30.0 - -15.1	10	6370	19.6%	48	420	20.2%	0	1455	18.6%	-58	895	12.7%	*3*	*9140*	*18.5%*
-15.0 - -0.1	159	8035	24.8%	206	547	26.3%	194	2214	28.3%	194	2584	36.6%	*173*	*13380*	*27.1%*
0 - 15.0	355	8343	25.7%	394	571	27.4%	412	2230	28.5%	506	2555	36.2%	*394*	*13699*	*27.7%*
15.1 - 30.0	606	6519	20.1%	625	421	20.2%	660	1516	19.4%	827	934	13.2%	*638*	*9390*	*19.0%*
30.1 - 45.0	884	1571	4.8%	830	63	3.0%	994	220	2.8%	1196	41	0.6%	*902*	*1895*	*3.8%*
45.1 - 60	1304	22	0.1%	1300	1	0.0%	0	0	0.0%	1345	1	0.0%	*1306*	*24*	*0.0%*
	291	**32419**	**100.0%**	**320**	**2082**	**100.0%**	**321**	**7824**	**100.0%**	**361**	**7060**	**100.0%**	***307***	***49385***	***100.0%***

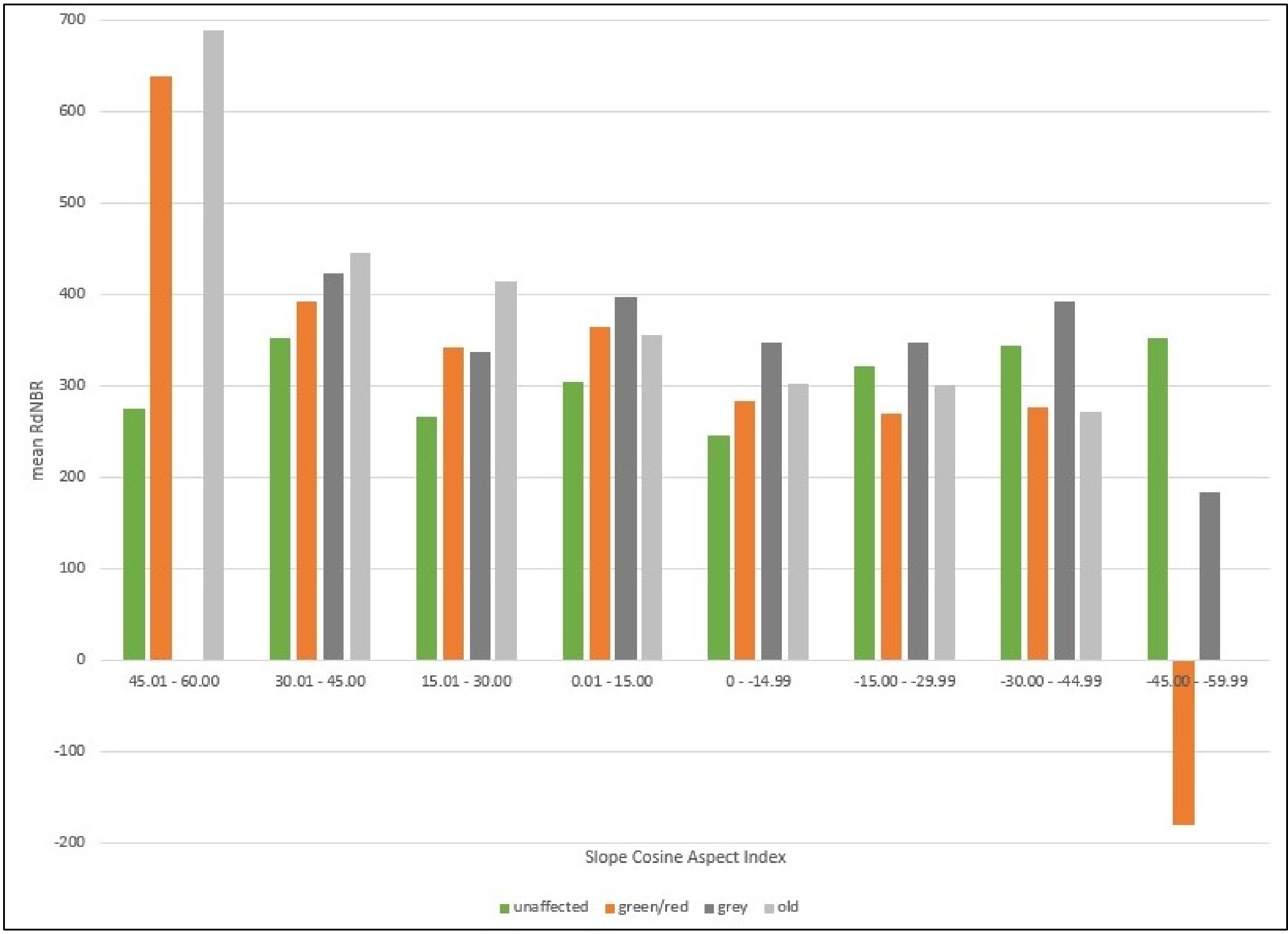


Figure 5. Mean RdNBR for each Slope-Cosine-Aspect Indexclass. RdNBR values: Enhanced Regrowth, High (-550 to -251), Enhanced Regrowth, Low (-250 to -101), Unburned (-100 to 99, Low Severity (100 to 269), Moderate-low Severity (270 to 439), Moderate-high Severity (440 to 659), High Severity (660 to 1350).

5. Discussion

Forest areas that experienced beetle-attack less than three years prior are generally believed to be at greater risk of fire ignition and high fire intensity, a characteristic that is associated with high burn severity. The proposed mechanism for this prediction is the change in moisture content and chemical composition of dead and dying needles on beetle-killed trees. These trees start to rapidly shed their needles approximately three years after MBP attack which have turned grey at this point, gradually reducing its canopy bulk density. By year five, the trees are completely denuded. Based on these processes, a reasonable prediction is that fires would burn with higher burn severity in forests in the early stages of beetle-caused mortality, burn with lower severity as these trees transition to grey-stage, and then finally burn with the lowest severity once transitioning to old-stage. Declines in canopy bulk density from needle fall may also lead to increased burn severity, as reduced crown foliage lowers the source of drag on wind, producing channelized wind flow when there is continuity in beetle outbreak, while also increasing surface fuels. However, the results observed in this study indicate that the opposite occurred: a greater proportion of forests over five years after a MBP outbreak (17.5%) burned in the high severity range, compared to forest in the grey stage (11.9%), green/red stage (9.6%), or unaffected stands (10.6%). This could possibly be linked to the disparity in sample sizes among different time since outbreak classifications and stands that were unaffected by MPB-outbreaks (49,385 total pixels), as the MPB-killed pixels (16,966 pixels or 34.4% combined) accounted for significantly lower point-total when compared to unaffected pixels, which made up 65.6% (32,419 pixels). Green/red stage represented 4.2% (2,082 pixels), 15.8% for grey-stage (7,824 pixels), and 14.3% for old-stage (7,060 pixels).

Another potential explanation for the higher burn severity values found in old-stage stands is the change of understory growth rate and structure following a MPB outbreak. Surviving canopy and sub-canopy lodgepole pine also experience enhanced growth rates, particularly in stands with higher MPB outbreak severity (Amoroso et al. 2013), but younger age-classes of understory lodgepole pine were found to be the most responsive following an outbreak (Hawkins et al. 2013). As the outbreak gradually reduces the overstory canopy cover, the understory begins to experience accelerated growth driven by an increase of sunlight and water availability, which can promote the growth of understory vegetation (Moritz et al. 2012). Once the old-stage begins when the dead trees are completely bare of needles, the understory experiences increased productivity, which could last 10-20 years following the disturbance (Amoroso et al. 2013). The needles add to the fine fuel accumulation on the forest floor. Also, the dead trees begin to fall over due to windfall or decay within five years of outbreak (Hicke et al. 2012), adding to the build-up of woody fuels on the forest floor. All of these factors may help establish understory-canopy continuity, acting as efficient ladder fuels to ignite the canopy (Hicke et al. 2012), which is associated with high burn severity.

One variable that was not available in the most recent version of the ADS data was outbreak severity, which had been available for previous studies. Harvey et al. (2012) found variable influence of outbreak severity over two different studies. One study suggested that outbreak severity affected few measures of fire severity (Harvey et al. 2014b), while the other found that outbreak severity was linked to fire severity, but that it was dependent on outbreak stage, with fire severity significantly higher in stands in the early stages of the outbreak (Harvey et al. 2014a). It is recommended for future studies to investigate the influence of outbreak severity on burn severity once these data are again made available.

Also, it is suggested that vegetation indices, such as Normalized Difference Vegetation Index (NDVI) or Red-Green (RGI) Index be investigated to assess their utility in determining understory vegetation growth. An initial attempt was made to use NDVI or RGI in locating MPB-killed stands in a portion of the study area, but the results yielded were inconclusive. Testing for spatial autocorrelation and multiple linear regression for each variable should also be investigated further. Moran’s I tests and multiple linear regression modeling were attempted during this study, but they yielded results that were statistically insignificant.

6. Conclusion

Time since outbreak and vegetation cover were more important influences on burn severity compared to topography (i.e., the slope-cosine-aspect index) across the 34 fires sampled in 2012. The findings indicate that old-stage stands had the highest burn severity of the three MPB-killed stand age classes, where it was initially expected that to have the lowest. This may be attributed to a smaller sample size of MPB-killed stands when compared to unaffected stands, or changes in understory growth rate and structure following a MPB outbreak. Enhanced productivity may increase understory flammability, while also establishing understory-overstory continuity, connecting ladder fuels that ignite canopy fires associated with higher burn severity. Hicke et al. (2012) suggested that in grey and old stage trees, increased surface fuel loads increase surface fire probability, and may decrease crown fire probability due to a reduction in canopy bulk density. But, increased torching potential may occur following increased surface fuel loads. As more outbreak areas continue to transition to old-stage, understanding the dynamics that drive burn severity in these areas (including green/red stage and grey-stage) will be important in maintaining firefighter safety, wildfire management planning, and anticipating ecological impact. It is suggested that future studies incorporate MPB outbreak severity in their analysis, if these data again become available through the ADS program, in addition to investigating the influence of rapid understory growth following MPB outbreaks and fire weather conditions.

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