THESIS

MOUNTAIN PINE BEETLE-CAUSED LODGEPOLE PINE MORTALITY FROM THE 1980'S AND SUBSEQUENT FIRE OCCURRENCE IN COLORADO

Submitted by

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WE HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER OUR SUPERVISION BY DANIEL R. WEST ENTITLED MOUNTAIN PINE BEETLE-CAUSED LODGEPOLE PINE MORTALITY FROM THE 1980'S AND SUBSEQUENT FIRE OCCURRENCE IN COLORADO BE ACCEPTED AS FULFILLING IN PART REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE.

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ABSTRACT OF THESIS

MOUNTAIN PINE BEETLE-CAUSED LODGEPOLE PINE MORTALITY FROM THE 1980'S AND SUBSEQUENT FIRE OCCURRENCE IN COLORADO

A need for understanding the interaction between post-epidemic bark beetle forest stands and subsequent fire occurrence has escalated due to recent (1999-2010) unprecedented epidemic mountain pine beetle in lodgepole pine (*Pinus contorta*) forests of Colorado. Outbreaks of mountain pine beetle *(Dendroctonus ponderosae* Hopkins) populations in the early 1980's resulted in substantial tree mortality across Colorado and provide a means to study past outbreak areas and subsequent fire occurrence. Beetle outbreaks on the Arapaho National Forest (NF) (1980-1987) and the White River National Forest (1981-1987), delineated by the USDA Forest Service Aerial Detection Survey (ADS), indicated approximately 76,900 ha were affected, with approximately 450,000 trees killed per forest. Mountain pine beetle-caused tree mortality is generally thought to increase subsequent fire occurrence and intensity but little scientific research supports this hypothesis. Thus, my objectives were to 1) determine whether there were differences in fire occurrences between lodgepole pine forests in Colorado, impacted or not impacted by previous outbreaks of *D. ponderosae* and 2) determine if fire occurrences in areas with mountain pine beetle-caused lodgepole pine mortality were related to topographic attributes, ignition type, and meteorological conditions.

We used historic USDA Forest Service Aerial Detection Survey maps (1980 – 1990) in conjunction with USDA Forest Service digital fire location records to look for mountain pine beetle and ignition relationships. Sixty eight maps were scanned to spatially identify *D. ponderosae*-caused mortality in lodgepole pine forests over the Arapaho NF and White River NF. Using a GIS, the spatial relationship between mountain pine beetle-caused mortality areas and subsequent fire occurrence was identified. During the summer of 2008, 57 ignition points were field assessed on the Arapaho NF and White River NF to verify the presence of mountain pine beetle-caused mortality prior to the fire as well as confirm the location of the recorded fire. Two of the 57 ignition points had evidence of trees killed by mountain pine beetle prior to the ignition.

Tests for independence of fire occurrence and mountain pine beetle-caused mortality were conducted for the Arapaho NF and White River NF. Combined human and lightning-caused fire densities did not differ (α=0.05) between areas with and without mountain pine beetle-caused mortality on the Arapaho NF, however, there were more fires in areas with mortality from the mountain pine beetle than non-impacted areas on the White River NF. Densities of lightning-caused fires alone did not differ between non-buffered and 50 m buffered mountain pine beetle-caused mortality areas and areas outside the mortality on the Arapaho NF or White River NF.

Logistic regression was used to model the probability of an ignition occurring within the area of the 1980's mountain pine beetle-caused lodgepole pine mortality on each forest. Elevation of fire occurrence was the most significant variable explaining the co-occurrence of fire with mountain pine beetle-caused mortality. Spatial autocorrelation was significant within human and lightning-caused fires but not lightning-caused fires alone. Thus, lightning-caused fires were used to eliminate the non-random nature of human-caused fires. Probability density functions were created using elevation ranges of mountain pine beetle-caused lodgepole pine mortality, lightning-caused fires prior to 1980, and elevations of fire occurrences intersecting aerially detected mountain pine beetle-caused mortality post-1980 through 2005 (during and post-outbreaks) to identify areas of highest probability independent of one another. Maximum probabilities for the occurrence of a lightning fire in a 1980's mountain pine beetle-caused mortality area within the Arapaho NF was between 2710 m and 2815m while on the White River NF the highest probability was between 2600 m and 2900 m. Probability density functions for a lightning fire occurring in an area with mountain pine beetle-caused mortality were applied across each National Forest using a GIS.

Our analysis suggests that 1980's mountain pine beetle-caused lodgepole pine mortality has not contributed to an increase in fire frequency over the subsequent twenty five years. The variability in fire occurrence and the homogeneity of mountain pine beetle outbreak-caused mortality, past and present, between the Arapaho NF and White River NF demonstrates the limited nature of comparability of this study to other locations.

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Introduction

The recent mountain pine beetle (*Dendroctonus ponderosae* Hopkins (Coleoptera: Curculionidae: Scolytinae)) epidemics (1999-2010) in lodgepole pine forests of western North America are the largest in magnitude and extent on record. Colorado, in particular Grand County, has experienced an exponential increase in lodgepole pine mortality since the late 1990's. Fire risk in mountain pine beetle areas is of concern to many stakeholders in Colorado. This study addresses the occurrence of fires within and outside areas with mortality from previous mountain pine beetle outbreaks in Colorado lodgepole pine.

Rocky Mountain lodgepole pine (*Pinus contorta* var. *latifolia* Engelm. ex S. Watson), ponderosa pine (*Pinus ponderosae* C. Lawson), and limber pine (*Pinus flexilis* James) are the major host species in Colorado for the mountain pine beetle. Suitable hosts of the mountain pine beetle comprise many species of pines (Furniss and Carolin 1977), of which whitebark pine (*Pinus albicaulis* Engelm.), Coulter pine (*Pinus coulteri* D. Don), sugar pine (*Pinus lambertiana* Douglas), foxtail pine (*Pinus balfouriana* Balf.), bristlecone pine (*Pinus aristata* Engelm.), limber pine (*Pinus flexilis* James) and pinyon pine (*Pinus edulis* Engelm.) (Amman 1989) are notable. The greatest mountain pine beetle-caused mortality throughout the insect's range can be expected in lodgepole pine and ponderosa pine (Amman 1989, Olsen et al. 1996).

1.1 Lodgepole pine

Lodgepole pine (*Pinus contorta* Douglas ex Louden) is a major forest type along the continental divide of the central Rocky Mountains and is a major component in many habitat types throughout Colorado (Moir 1969; Little 1971) (Figure C1). Rocky Mountain lodgepole pine (*Pinus contorta* var. *latifolia* Engelm. ex S. Watson) is one of four subspecies (*Pinus contorta* var. *bolanderi*, Bolander beach pine; *Pinus contorta* var. *contorta*, beach pine; *Pinus contorta* var. *murrayna*, Sierra lodgepole pine) extending from its southern range in Colorado (Moir 1969; Little 1971) and Utah (Welsh 1987; Little 1971) (Figure 1) north to the Northwest Territories (Brouilet et al. 2006; Little, 1971). The collective subspecies of lodgepole pine can be found from sea level (Little 1971) to approximately 3,050 to 3,350 meters (Peet 1981) in Colorado while transitioning to spruce-fir above 3,660 meters of elevation (Lotan et al. 1985). Lodgepole pine (*Pinus contorta* Douglas var. *latifolia* Engelmann) stand initiation is typically associated with stand replacement fires and it is considered a fire maintained subclimax species (Brown 1975; Pfister 1975; Lotan et al. 1985; Arno 2000).

Lodgepole pine has adapted to high intensity, large-scale fire disturbance through cone serotiny, however both serotinous and non-serotinous individuals grow side by side in the same stands (Muir and Lotan 1985). Fire return intervals vary regionally from frequent, low-intensity 1 to 16 year intervals in Jasper National Park, Alberta, Canada (Tande 1979) to high intensity, 400 year stand replacing intervals in Yellowstone National Park, Wyoming (Romme 1982).

1.2 Mountain pine beetle

Mountain pine beetle can cause extensive mortality to lodgepole pine in western North America (Lotan et al. 1990; Safranyik 2006). This native insect's range is from Mexico to Alaska, and from the Pacific Ocean to the Black Hills of South Dakota (Amman 1989) (Figure 2). The elevation range of *D. ponderosae* is from sea level to approximately 3,650 m in Colorado (Safranyik 2006). Lodgepole pine stands possessing 750 to 1,500 trees/ha (Shore et al. 2000) with a mean age of ≥ 80 years old and mean diameter at breast height of ≥ 20 cm (8 in.) are most susceptible to infestation by mountain pine beetle (Amman et al. 1989). In Montana, lodgepole pine stands ranging from 60 to 125 years old, below 1,829 m of elevation, with basal area greater than 29.8 m^2/ha are considered to have the greatest risk of tree mortality from mountain pine beetle infestations (Bollenbacher and Gibson 1986). Thinning heavily stocked lodgepole pine stands has long been considered a practical strategy to reduce mortality from the mountain pine beetle (Furniss and Carolin 1977; McGregor and Cole 1985; Wood et al. 1985; Whitehead et al. 2004).

Adult *D. ponderosae* seek suitable hosts through the use of olfactory and visual cues (Campbell et al. 2006a; Campbell et al. 2006b), random landing (Burnell 1977; Hynum et al. 1980), or a combination of these (Pureswaran et al. 2003). Typical life cycles at lower elevations are univoltine, while semivoltine, completing one generation over two years can occur at high elevations. Larvae are able to prevent cold-induced mortality through the synthesis of glycol, which enables the mountain pine beetle to maintain populations through the winter (Langor, 1989). Extreme cold and phloem desiccation pose the biggest environmental threats to survival (Cole 1981; Safranyik 1989).

Symptoms of mountain pine beetle infestation include pitch tubes, resin accumulations released by the tree as the insect severs resin canals on the lower 5 m of the tree, copious amounts of frass in bark flakes and/or around the tree base, and crown fading. Mass attacks occur when pioneer females produce semiochemicals, which attract host searching individuals of both sexes. The ensuing mass aggregation occurs in late July through August (Safranyik 1989).

Females construct vertical, 25-30 cm long parental egg galleries in the xylem-phloem interface after successfully mating with a male at the gallery entrance. Eggs are laid in an alternating pattern along the sides of the gallery, typically 60-80 per female. A suite of fungi (*Ophiostoma clavigerum* (Robinson-Jeffrey & Davidson) Harrington and *O. montium* (Rumbold) von Arx), yeasts, and bacteria are introduced into the egg galleries. These organisms aid the beetle in staving off tree defenses (Safranyik 1989; Safranyik et al. 2006), provide nutrients for developing life stages, and congest conductive host tissues. Egg eclosion occurs within two weeks and larvae mine the phloem perpendicular to the egg gallery (Safranyik 1989). Crown fading typically takes two years and begins from the top of the tree and progresses downward in a color gradient from green, greenish-yellow, rust (reddish orange) to brown (Safranyik et al. 2006).

1.3 Bark beetle-fire interactions

Various authors throughout the literature suggest there is an increase in fire hazard (potential fire behavior (Hardy 2005)), fire risk (chance that fire occurs and the resultant damage (Hardy 2005)), or both after a mountain pine beetle epidemic (Hopkins 1909; Geiszler et al. 1980; Parker and Stipe 1993; Turner et al. 1999; Arno 2000). However, empirical data on fire occurrence is scant in areas with post-epidemic mountain pine beetle-caused mortality. Stand structure, microhabitat, species composition and successional stages can be transformed by epidemic populations of mountain pine beetle (Amman 1977; Gara et al. 1985; Shore et al. 2006; Sibold et al. 2007) which may affect post-epidemic fire behavior once an ignition has spread into the fuels. In northern Utah and central Idaho, Page and Jenkins (2007a) measured fuel in current epidemic mountain pine beetle stands and stands 20 years post-epidemic. Higher fine surface fuels were reported in the current epidemic stands with significant heavy fuels (1000 hr, > 7.6 cm diameter) in the 20 year post-epidemic stands. These findings are supported with more recent studies where Klutsch et al. (2009) reported litter depth was greater 4 to 7 years post-initial infestation compared to 1-3 years post-initial infestation on the Arapaho NF, Colorado. The epidemic in Colorado had not waned prior to or during their measurement period, so their results may be conservative in evaluating the overall fine fuel loading from epidemic mountain pine beetle populations in lodgepole pine stands.

Lodgepole pine in Yellowstone National Park, WY sustained a mountain pine beetle outbreak from 1972 through 1975 and subsequently was impacted by large scale fires in 1988 (Lynch et al. 2006). This outbreak increased the odds of an area burning by the 1988 fires by 11%, determined by the burn pattern within previous mountain pine beetle-caused mortality. However, an additional outbreak from 1980 through 1983 in the National Park did not show any significant increase in odds of burning by the 1988 fire.

Empirical models of fire behavior with measured fuel as inputs are used to examine potential fire behavior and fuel consumption if an ignition were to coincide with mountain pine beetle-caused fuels. Page and Jenkins (2007b) found through their fire behavior modeling that fuel loads and forest structure associated with twenty year old mountain pine beetle outbreaks decrease crown fire occurrence while current epidemic fuel loads and forest structure increased occurrences of canopy crowning fire type, individual tree torching, and surface fire spread rates. Klutsch et al. (unpublished) found similar modeling results in lodgepole pine type in the central Rocky Mountains of Colorado. Through empirical modeling, Klutsch et al. (unpublished) found differences in fire type as projected tree fall occurs in mountain pine beetle affected stands. Their results show a transition from crown fire in uninfested stands to individual tree torching and surface fire in stands with mountain pine beetle fuels, where the mountain pine beetle-caused mortality removed the continuity of the lodgepole pine canopy.

Studies in Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) in the Rocky Mountains have shown an influence of spruce beetle on fire return rates (Veblen et al. 1994; Bebi et al. 2003). After a 1997 Engelmann spruce blowdown disturbance in northern Colorado, outbreak spruce beetle (*Dendroctonus rufipennis* Kirby) populations had no detectable correlation with fire severity and extent five years later (Kulakowski et al. 2007). In spruce forests of central Colorado, it has been suggested that a drought would be required 2 to 3 years post-infestation to initiate an increase in widespread fire (Bebi et al., 2003). Bebi et al. (2003) found an increase over the expected fire return interval where a previous 1940 spruce beetle outbreak had occurred. In contrast, in white spruce (*Picea glauca* Moench) and Lutz spruce (*Picea lutzii* Little) forests of Alaska, a reconstructed radio-carbon dated soil charcoal fire history spanning ca. 2500 years found no relationship between spruce beetle outbreaks and fire activity (Berg and Anderson 2006). Derose and Long (2009) found, through empirical modeling of near pure

Engelmann spruce forest type in Utah, a reduced probability of active crown fire behavior in stands experiencing 95% spruce beetle-caused mortality.

Further, it has even been suggested that a natural cycle of mountain pine beetle and subsequent fire is the norm for unmanaged lodgepole pine (Koch, 1996; Schmidt, 1989). However, Shore et al. (2006) stated a lack of evidence exists in support of increased fire incidence in stands having sustained mountain pine beetle-caused mortality. Empirical knowledge regarding the interactions of coniferophagous insect-caused tree mortality and subsequent fire is by in large lacking in the scientific literature. Current mountain pine beetle outbreaks in lodgepole pine ecosystems raise hypotheses regarding the ecological processes of fuel production and changes in stand structure on subsequent wildfire. In this study we aim to examine the relationship between lodgepole pine forests having sustained outbreak mountain pine beetle-caused mortality, and the occurrence of subsequent fire in the north-central Colorado Rocky Mountains. We hypothesized that there would be no difference between observed and expected fire occurrences in lodgepole pine forests previously impacted by 1980's mountain pine beetle-caused mortality. Furthermore, we hypothesized that topography, fire attributes and weather conditions do not have an effect on whether or not fire occurrences follow mountain pine beetle outbreaks. Our specific study objectives were to 1) determine whether there were differences in fire occurrences between lodgepole pine forests in Colorado, impacted or not impacted by previous outbreaks of *D. ponderosae* and 2) determine if fire occurrences in areas with mountain pine beetle-caused lodgepole pine mortality were related to topographic attributes, ignition type, and meteorological conditions.

Materials and Methods

To address our research objectives, we needed spatially explicit mountain pine beetle outbreak data and fire locations in lodgepole pine that occurred several decades after the mountain pine beetle outbreaks. USDA Forest Service Annual Reports, USDA Forest Service Aerial Detection Survey (ADS), and USDA Forest Service fire point histories were used to locate study sites.

2.1 Study Areas

The Arapaho NF occupies 450,522 ha largely in Grand County, CO while the White River NF spans 833,871 ha having most of its area in Eagle County, CO. Stands dominated ($\geq$ 50% species composition) by lodgepole pine were selected from a spatial GIS covertype layer delineated from aerial images (Common Vegetative Unit; R2VEG). The Arapaho NF had approximately 102,050 ha of lodgepole pine dominated forest type between 2,377 and 3,552 m of elevation (Figure 5, Table B3). The White River NF had 48,910 ha of lodgepole pine forest type between 2,286 and 3,584 m of elevation (Figure 6, Table B3). The areas of the forests were based on USDA Forest Service forest boundary and cover type shapefiles projected in PCS NAD 1983 UTM Zone 13N.

2.2 USDA Forest Service Hardcopy Aerial Detection Survey

The USDA Forest Service, Region 2, Forest Health Management has conducted aerial surveys of forest lands recording tree damage from various insects and diseases in different host species since 1956. As a source of information, 30 hardcopy USDA Forest Service Aerial Detection Survey maps from the Arapaho (16) and White River (14) NFs were digitally scanned on a high-resolution-wide-format scanner to obtain 300dpi TIFF and JPEG images. Areas of mountain pine beetle-caused mortality on map images were digitized (georeferenced and rectified), which created (ArcGIS ArcMap, version 9.2) a polygon shapefile from the Arapaho (1980-1987) and White River (1981-1987) NFs. Attributes of each mortality polygon were recorded including the estimated number of lodgepole pine trees killed by the mountain pine beetle. Annual digitized shapefiles were aggregated to form a dataset containing the spatial location and attributes of the mountain pine beetle-affected areas on each National Forest (Figures 3, 4).

2.3 Fire Record

The historic fire record was used to locate occurrences of ignitions between 1933 and 2005 in areas with and without previous mountain pine beetle activity. Digital spatial datasets were obtained from various District Offices, Forest Supervisors' Offices and the Regional Office of the USDA Forest Service, Rocky Mountain Region. Fire records included fire perimeter polygons and/or point of occurrence. Fire perimeter records were scarce prior to 2000, therefore we used single point fire location records (Figure C2; Table B4). Each fire record had associated attributes including, but not limited to, the fire identification number, year, fire size, and cause.

2.4 Mapping - Geographic Information System

The digital spatial data layer of aerial surveyed beetle-induced mortality from 1980 through 1987, the fire point record from 1933-2005 (Arapaho NF 1958-2005; White River NF 1933-2003), and the lodgepole pine dominated covertype (USDA Forest

Service, R2Veg shapefile) for each USDA Forest Service National Forest were displayed using ESRI's ArcMap software (versions 9.1, 9.2.1). We designated fire ignitions in lodgepole pine stands on both forests that occurred within and outside perimeters of prior mountain pine beetle-caused lodgepole pine mortality (1980-1987). Attributes of each fire included the coordinates, size, date, cause, and the yearly aggregated occurrence of ADS mountain pine beetle-caused mortality polygons. Lightning fires that occurred prior to the mountain pine beetle-caused mortality (1933-1979) were selected as another dataset. We used the following fire occurrence datasets: 1) fires that occurred after 1980 were used to test fire densities for independence with and without mountain pine beetle-caused mortality areas and to statistically model fire occurrence with mountain pine beetle-caused mortality areas 2) fire attributes (1980-2005) and presence of aggregated annual ADS lodgepole pine mortality or lack thereof were used in the field assessment for locating fire and mountain pine beetle-caused mortality 3) lightning fires that occurred prior to the mountain pine beetle-caused mortality (1933-1979) were used in probability density functions (see Data Analysis 3.5).

2.5 Field Assessment

Field verification in 2008 documented the presence of coarse fuels having resulted from outbreak mountain pine beetle events and subsequent fire ignition in the same location. Fires intersecting mountain pine beetle-caused mortality areas were selected for field assessment. Additionally, fires adjacent to (within 2 km) mountain pine beetle-caused mortality polygons were included in the field assessment to incorporate potential omission error from the aerial survey. Fire points occurring post mountain pine beetle-caused mortality were visited by field assessments at their GPS coordinates. If fire signs were located at the coordinates, we surveyed the forest in cardinal directions to determine the extent of visible fire signs. If no fire signs were evident at the point, we searched for 400 m in all cardinal directions until fire signs were located. Fire signs included remnant standing or downed coarse woody debris with residual charcoal. Once the extent of fire sign was determined in all cardinal directions, the area within the fire signs was cruised for coarse woody debris large enough to be a result of previous mountain pine beetle attack (Figure C3). Previous work in whitebark pine supports the field methods of identifying remnant coarse woody debris with signs of bark beetle mortality via egg galleries (Perkins and Roberts 2003). Each debris remnant that was at least 10 years dead was inspected for evidence of mountain pine beetle egg gallery engraving of the xylem tissue. To ensure that we did not record dead trees from a recent outbreak, downed woody debris having less than 50% of the1-hour and 10-hour time-lag fuels (0 to 2.54 cm in diameter) attached to the tree was assumed to be 10 years or older since mortality. Downed woody debris showing evidence of having burned within the identified fire were recorded (Fig. 7).

The total number of downed woody debris pieces in the 1000-hour fuel time-lag class (Helms 1998) (downed woody debris greater than 7.6 cm in diameter) with evidence of mountain pine beetle-caused mortality within the cardinal direction surveys was recorded. Fires with four or more downed 1000-hour woody debris pieces with signs of previous mountain pine beetle infestation were classified as associated with previous mountain pine beetle mortality.

Data Analysis

3.1 GIS buffering and fire point density

Johnson and Ross (2008) indicated that the spatial accuracy of aerial detection surveys of mountain pine beetle in lodgepole pine was 70% and increased by 10% and 7% when buffered by 50 and 500m, respectively. Therefore, we buffered the aerially detected mountain pine beetle polygons by 50 m to account for locational error in the Aerial Detection Survey. We elected to not incorporate a 500 m buffer since it increased the area of mountain pine beetle-caused mortality by 1.8 times that of the non-buffered mortality area. To calculate fire density in the area affected by the mountain pine beetle, the annual mortality polygons were aggregated from 1980-1987 to form contiguous polygons of observed lodgepole pine mortality plus the 50 m error buffer (Figures C4, C5). The total area of the merged polygons was calculated to determine fire density within and outside of the mortality polygons. Fire occurrence was summed for ignitions intersecting the non-buffered mountain pine beetle-caused mortality polygons and the 50 m buffered polygons as well as fire occurrences outside of the areas with mortality. The same approach was used to calculate fire occurrence outside of the mortality areas and chi square tests of independence were calculated by the area affected by lodgepole pine mortality and were performed on each mortality buffer category using combined human and lightning caused fires and lightning only caused fire occurrences.

Chi square tests were modeled:

$$X^2 = \frac{(O_a - EXP_a)^2}{EXP_a} + \frac{(O_b - EXP_b)^2}{EXP_b}$$

where O_a was the observed frequency of fire occurrence with mountain pine beetle-caused lodgepole pine mortality and EXP_a was the calculated expected frequency of fire occurrence with mountain pine beetle-caused lodgepole pine mortality. Variable O_b was the observed fire frequency without intersecting polygons of aerially detected mountain pine beetle-caused lodgepole pine mortality. Term EXP_b was the expected fire occurrence without intersecting any mountain pine beetle-caused lodgepole pine mortality polygon. EXP_x was calculated as:

$$EXP_x = F(\frac{A_1}{A_2})$$

Variable F was the frequency of observed fires from lodgepole pine on each National Forest. Term A_1 was the aerially observed mountain pine beetle-affected area (sq. meters) from x National Forest. Term A_2 was the total area of National Forest x, for both mountain pine beetle-affected areas and uninfested areas.

3.2 Probability of fire ignition occurring with mountain pine beetle area

Logistic regression was used to model the likelihood of human and lightning fire occurrence within mountain pine beetle-caused mortality polygons using fire and geographic attributes (Proc Logistic; SAS v9.2). Stepwise selection process was used to distinguish variables significant to enter or stay in the model at alpha 0.10. Variables explored in the model were National Forest where each fire occurred, year of fire, fire cause, $\log_{10}$-transformed fire size, elevation (m), percent slope, aspect category, $\log_{10}$-

transformed distance to nearest road, an interaction term between forest and elevation, and the quadratic term of elevation^2 was added to allow for any potential curvilinear relationship to be elucidated. The final (alpha= 0.05) model used five variables; mountain pine beetle occurrence (0, 1), as a function of Forest, elevation, Forest * elevation, and elevation^2. Spatial variance of the residuals from the final model were tested for spatial autocorrelation and found to not be correlated, eliminating the need for spatial adjustment in the model. Pairwise comparisons of mean elevations and medians were calculated between National Forests with the presence/absence of mountain pine beetle-caused mortality areas. There were too few lightning-caused fires within beetle mortality areas on either forest relative to fires outside beetle mortality areas to perform a logistic model.

3.3 Fire cause

Lightning and human-caused fire occurrences were independently selected for a comparative analysis looking at differences in elevation with and without mountain pine beetle-caused mortality areas (Table B5). The linear model took the form of fire elevations as a function of National Forest and fire cause. Pairwise comparisons of mean and median elevations of combined lightning and human initiated fires were tested for differences with and without mountain pine beetle-caused mortality within National Forests using the Kruskal-Wallis test at an alpha of 0.05. Spatial variance was tested to determine if the variability between lightning-caused fires and human-caused fires was spatially homogeneous across the fire points.

3.4 Stand Inventory Analysis of Mountain Pine Beetle-caused Mortality

Stand inventory records for stands with 20% or greater lodgepole pine basal area were obtained from the USDA Forest Service, Region 2 to quantify the density of standing mortality in mountain pine beetle-caused mortality areas (1980-1987). We selected stands inventoried in 1978 (to capture any mortality that may have occurred two years prior to 1980 aerially detected mountain pine beetle-caused mortality) through 1993, six years after the mountain pine beetle outbreak (when trees were likely to be standing dead as a result of the mountain pine beetle). Trees greater than 12 cm in dbh (diameter at breast height) were selected yielding tree diameter classes with the greatest probability of infestation by the mountain pine beetle. Stands intersecting areas of aerially detected mountain pine beetle-caused lodgepole mortality were selected using ESRI's ArcMap (version 9.3.1) intersect tool. A new variable (mpb=yes or no) was created from the intersection designating stands having intersected the observed mountain pine beetle-caused mortality polygons. Trees/ha were summed for live or dead trees within each plot within each stand. Standing live and dead trees/ha was averaged across areas within and outside of the mountain pine beetle-caused lodgepole mortality intersection. Stand basal area was summed across plots within stands, and averaged across stands intersecting mountain pine beetle-caused mortality.

3.5 Probability Density Function Surface

To estimate probabilities of where lightning fires and mountain pine beetle are likely to occur independent of one another, probability density functions were created from fire occurrence information on each National Forest. Since mountain pine beetle activity is related to elevation on the Arapaho and White River NFs, probability density functions were based on elevations of historical fire and mountain pine beetle events and applied to a GIS. The probability density functions are represented by a curve such that the area under the curve between two elevations is the probability that the variable will be between those two elevations. Spatial probability surfaces were created from the probability density functions based on elevations of the mountain pine beetle-caused mortality polygon centroids (1980-1987), lightning-caused fires prior to the outbreak (1933-1979), and where lightning-caused fires and mountain pine beetle areas co-occur (1980 through 2003; 2005). Probability density functions for the 1980 through 2005 fire elevations occurring with previous mountain pine beetle-caused mortality areas were calculated separately to remove any influence of fire frequency after the mountain pine beetle outbreak from the final joint probability density functions. Spatial autocorrelation was determined to be significant within human-caused and lightning-caused fires as a function of elevation but not lightning-caused fires alone. Therefore, only lightning-caused fires were selected for analysis due to the autocorrelation. A cumulative distribution function was calculated (R, Classification Regression and Analysis Network; version 2.10.1) for the elevation rank of each mountain pine beetle-caused mortality polygon, pre-mountain pine beetle infestation fire points caused by lightning (prior to 1980), and the intersection between the lightning fire points occurring within the mountain pine beetle-caused mortality polygons (post-1979).

$$\pi = \frac{e^{(\beta_0+\beta_1 X+\cdots)}}{1+e^{(\beta_0+\beta_1 X+\cdots)}}$$

The cumulative distribution function is greater than 0 and less than 1. The logit function was calculated and further modeled using a general linear model (GLM) to find the best fit model to the fifth degree polynomial.

Logit:

$$logit = ln\left(\frac{\pi_i}{1 - \pi_i}\right), \quad -\infty < logit < \infty$$

GLM:

$$X = \beta_0 + \beta_1 E + \beta_2 E + \cdots$$

Model selection was based on the lowest AIC values. The first derivative of the cumulative distribution function provided an estimate of the probability density function. The probability density function is given by:

$$pdf = \frac{X' \exp(X)}{(1 + exp(X))^2}$$

where *X'* is the first derivative of *X*.

The joint probability was modeled:

P(L,B)=P(L)*P(B)+P(LB)

where P(L) is the probability density function of lightning-caused fires as a function of elevation and P(B) is the probability density function of beetles occurring as a function of elevation and P(LB) is the probability density function of both lightning-caused fires and mountain pine beetle-caused polygons occurring together as a function of their elevation.

3.6 Drought indices and fire frequency

A hypothesis among scientists based on logic suggests fire hazard is greatest when trees attacked by mountain pine beetle retain their needles, followed by a sharp decrease in hazard when the needles have abscised and the tree is standing dead. Once tree-fall has occurred, the idea follows that fire risk gradually increases as the 1000-hour fuels accumulate and become dry on the forest floor. We wanted to quantify the temporal scale of fire occurrence in mountain pine beetle-caused mortality areas in relation to the given set of meteorological conditions for the purpose of identifying expected years of greater fire frequency. Annual fire occurrences were compared with regional meteorological conditions using a drought index in conjunction with calculated annual chi square statistics. This analysis identified significant years of fire occurrence with mountain pine beetle-caused lodgepole pine mortality. We obtained the Modified Palmer Drought Severity Index (PMDI) data for 1950 through 2008 for Rocky Mountain Regions 24 and 25 (Colorado Climate Center) (Figures C6, C7, C8, and C9). Annual maximum and minimum PMDI were selected for Colorado Regions 24 and 25 from 1980 through 2008 (Figure C10). Annual cell chi squares were calculated using the frequency procedure (Proc Freq; SAS version 9.2) on annual fire occurrence intersecting mountain pine beetle-caused lodgepole pine mortality. Annual cell chi squares were graphed based on positive or negative deviation (directional) of expected fire frequency to identify possible correlations between annual PMDI and annual fire frequency in areas of mountain pine beetle-caused lodgepole pine mortality and uninfested areas.

Results

Multiple outbreaks of mountain pine beetle in lodgepole and ponderosa pine occurred between 1956 and 1990 on the Arapaho, Roosevelt, Uncompahgre, Grand Mesa, Medicine Bow, Pike San Isabel, Routt and White River National Forests. Most outbreaks were short in duration (less than 5 years) (Table B1) and covered a limited area. We selected the outbreaks on the Arapaho NF and White River NF since these forests had sustained outbreaks (1980-1987) and wide-reaching (more than 100,000 ha) mountain pine beetle activity in lodgepole pine forests.

4.1 Hardcopy USDA Forest Service Aerial Detection Survey

The mountain pine beetle outbreaks on the Arapaho and White River NFs were selected based on their spatial and temporal reference learned from the digitizing process. The Arapaho NF and surrounding private or other ownership land had 1,657 aerially detected mortality polygons from 1980 through 1987. The elevation of mortality polygon centroids ranged from 2,226m to 3,477m occupying 78,453 ha with an estimated 432,638 affected trees (Figure 8). However, only 467 mortality polygons (28.1 percent) occurred within the Arapaho NF boundary occupying 22,724 ha and 92,170 trees (Figure 3). The remainder of the mountain pine beetle-caused mortality occurred on private or other ownership lands. Both mortality area and tree mortality counts are estimates of the infestation intensity, not precise measurements, as the objective of the aerial detection flights is to document landscape-level trends of insect and disease activity.

The White River NF and surrounding private and other ownership land had 1,463 aerially detected polygons of mountain pine beetle-caused lodgepole pine mortality from 1981 through 1987. Mortality polygon centroid elevations ranged from 2,161m to 3,568m covering 79,922 ha with an aerially estimated total tree mortality of 451,659 (Figure 8). The majority (88.1%) of the White River NF mountain pine beetle-outbreak occurred within the NF boundary with an estimate of 424,788 trees (Figure 4).

4.2 Fire occurrence and Density

The Arapaho NF had a total of 530 ignition points from 1930 through 2005 across all cover types. From 1980 through 2005, the Arapaho NF had 263 ignitions in lodgepole pine forests. These were used to assess the co-occurrence of previous mountain pine beetle-caused mortality. The White River NF had 2,670 ignition points in all cover types from 1933 through 2003 of which 203 ignitions occurred in lodgepole pine forests from 1980 through 2003. Fourteen human and lightning ignitions occurred in areas of lodgepole pine impacted by mountain pine beetle on the Arapaho NF between 1980 and 2005 while 43 ignitions occurred on the White River NF.

4.3 Field Assessment

Fifty seven fire points that occurred after 1979 were field assessed on the Arapaho NF (34) and White River NF (23). Nine ignitions on the Arapaho NF intersected the areas with mountain pine beetle-caused mortality. The field assessment found two of these nine ignitions had evidence of prior mountain pine beetle mortality. No evidence of prior mountain pine beetle-caused mortality was observed at the 25 fires on the Arapaho NF adjacent to (within 2000m), but not intersecting, the outbreak area (Figure C11). Five additional fire points were undetermined as to whether the ignition had occurred with mountain pine beetle-caused mortality fuels due to either errors in the point location, forest activities, or adverse terrain conditions.

We field assessed 23 ignitions on the White River NF that occurred within mountain pine beetle-caused mortality areas (Figure C12) and none had evidence of previous mountain pine beetle-caused fuels.

4.4 Fire point density and GIS buffering

The Arapaho NF experienced 263 human and lightning-caused fires in lodgepole pine stands from 1980 through 2005. Without allowing for spatial detection errors, fourteen fire points intersected the lodgepole pine-mountain pine beetle-caused mortality polygons. Buffering the polygons by 50 m resulted in additional 4 fires within mountain pine beetle-caused mortality polygons. The area occupied by the non-buffered mortality was 5% of the National Forest, while increasing the mortality buffer to 50 m increased the affected area to 5.5%. While buffering the mortality polygons increased the overall area in the 50 m, chi square tests for independence showed no differences between Arapaho NF observed and expected fire frequencies across mortality area categories (Table 1).

The observed human and lightning-caused fire frequency for the White River NF was 43 within and 160 outside of the mountain pine beetle-caused mortality polygons. Observed fire occurrences within the mountain pine beetle-caused mortality areas (non-buffered and buffered) on the White River NF were greater than their expected fire occurrences across buffer categories (Table 1).

Fire frequencies from lightning-caused ignitions on the Arapaho NF and White River NF were tested for independence from the mountain pine beetle-caused lodgepole pine mortality (1980-1987). Chi square tests for independence were conducted on ignitions that intersected the non-buffered and 50 m buffered lodgepole pine mortality polygons and ignitions not intersecting the mortality areas (Table 2). No differences occurred on the Arapaho NF between lightning-caused fires intersecting areas with previous mountain pine beetle-caused lodgepole pine mortality and lightning-fires not intersecting the lodgepole pine mortality. The White River NF lightning-fire frequency intersecting the non-buffered and 50 m buffered mountain pine beetle-caused mortality areas were independent (Table 2).

4.5 Probability of fire ignition occurring with mountain pine beetle area

The logistic regression model selected forest, elevation, elevation^2 and forest * elevation predictor variables to model the probability of a human or lightning caused fire occurring in areas with previous mountain pine beetle-caused mortality on the Arapaho NF and White River NF. Elevation was the primary driving variable and across both forests, the model predicted a greater probability of mountain pine beetle-caused mortality presence at a given fire point at lower elevations (Table 3, Figure 9). The optimal threshold (maximizing true positives and minimizing false positives) probability was 0.17, with a model accuracy of 74%. Fire points with a probability below 0.17 would be modeled as occurring without mountain pine beetle occurrence (Figure 10). The area under the receiver operator classification (ROC) curve (AUC=0.818) indicates the model performance in separating fire occurrence with and without mountain pine beetle-caused mortality (Figure 11). AUC values between 0.8 and 0.9 indicate good performing models.

The mean elevation of fires occurring within the mountain pine beetle-caused mortality across both forests was significantly lower (2803 m± 31.4) (Mean ± SE) compared to mean fire elevations occurring without mountain pine beetle-caused mortality (2990 m ± 10.3). The mean elevations of all fires on the White River NF (2942.2 m ± 17.5) were higher than fires on the Arapaho NF (2850.9 m ± 28.0) (p-value 0.006). Elevations of lightning-caused fires on the Arapaho NF were higher (3010 m ± 24.2) than human-caused fires (2936.4 m ± 15.2). Median lightning-caused fire elevations (3019 m ± 23.6; Median ± SE) for the Arapaho NF were higher than the median human-caused fire elevations (2911 m ± 14.3).

Average White River NF lightning-caused fire elevations (3001.1 m ± 27.8) were not different than average human-caused fire elevations (2973.6 m ± 17.3). Median lightning-caused fire elevations (3013 m ± 14.3) for the White River NF were not different than median human-caused fire elevations (2984.5 m ± 17.8).

4.6 Fire size and cause

The majority of all fires occurring on the Arapaho NF and White River NF, irrespective of an intersection with previous mountain pine beetle areas are very small (< 0.4 ha). The cumulative percent of fires 0.4 ha or smaller on the Arapaho NF and White River NF that occurred in areas with mountain pine beetle-caused mortality was 85.7% and 95.3%, respectively. The cumulative percent of fire occurrences smaller than 0.4 ha outside of the mountain pine beetle-caused mortality polygons was 92.4% and 94.4% for the Arapaho NF and White River NF, respectively (Tables 4, 5).

The mean size of fires on the Arapaho NF occurring within the area of mountain pine beetle-caused mortality polygons was 0.41 ha ± 4.78 (mean ± SE) with mean size of fires not intersecting the mountain pine beetle areas was 1.68± 1.13 ha (Table B6). The White River NF had an average fire size of 0.10 ha ± 2.73 within the mountain pine beetle-caused mortality areas whereas the size outside of the mountain pine beetle-caused lodgepole pine mortality was 1.86 ha ± 1.41 (Table B7). However, the fire population was too small and skewed towards the preponderance of small fires to test for relationships between factors related to forest and mountain pine beetle presence and size of fire (Tables 4, 5).

The Arapaho NF had 75 lightning-caused fires and 188 human-caused fires between 1980 and 2005. Seven lightning fires and seven human-caused fires occurred in the mountain pine beetle-caused mortality areas. The White River NF had 57 lightning-caused fires and 146 human-caused ignitions (1980-2003). Six lightning-caused fires and 37 human-caused fires occurred within the mountain pine beetle-caused mortality areas.

4.7 Stand Inventory Analysis

The only direct measurement of mortality on the Arapaho NF during 1978 through 2003 came from 4,171 resource inventory plots established within stands with 20% or greater basal area in lodgepole pine by the Forest Service (Table B8). Intersecting mountain pine beetle-caused mortality polygons resulted in 2,221 stands on the Arapaho NF. (Figure C13). Of these, 885 stands were inventoried between 1978 and 1993 containing 25.9% of the measured plots (4,171 plots) (Table B8). Average Arapaho NF standing dead trees/ha (1978-1993) of species in areas of mountain pine beetle-caused mortality was 8.7%

whereas outside of the mountain pine beetle-caused mortality areas stands had 7.8% standing dead trees/ha (Table 6). Both live and dead standing basal areas of all species were lower in stands intersecting mountain pine beetle areas by 3.0 m^2 and 0.2 m^2, respectively (Table 7). When only lodgepole pine species were selected, average dead standing trees/ha were lower by 10 trees/ha (58.6 trees/ha) while the average live standing trees/ha went down by 86.3 trees.

The White River NF had 5,369 stands that occurred within the ADS mountain pine beetle-caused mortality areas (Figure C14). A total of 1,009 stands in lodgepole pine were measured from 1978 through 1993 with 34.1% of the plots (5,672 plots) occurring in mountain pine beetle-caused mortality polygons (Table B8). Average White River NF all species standing dead trees/ha in areas of mountain pine beetle-caused mortality was 9.6 % while outside of the mountain pine beetle-caused mortality areas there was 7.3% standing dead trees/ha (Table 6). On the White River NF, average basal area of standing dead and standing live trees was greater in stands intersecting mountain pine beetle-caused mortality by 1.0 m^2 and 3.1 m^2, respectively (Table 7). When only lodgepole pine species were selected within stands intersecting mountain pine beetle-caused mortality areas, trees/ha was reduced by 219.9 and 25, respectively (Table 6).

4.8 Probability Density Function Surface

The Arapaho and White River NFs mid-elevation probability density function quartiles had the greatest probability of mountain pine beetle-caused lodgepole mortality (1980-1987) and lightning-caused fires co-occurring (Table 8; Figures 12, 13). The second and third quartiles of the Arapaho NF joint probability surface had a total 16,397 ha of dominated lodgepole pine forest between 2,710 and 2815 m of elevation with probability density functions between 0.0031 and 0.004 (Table 8). The Arapaho NF joint probability density function mode occurred in the third quartile (based on the cumulative distribution function) at 0.0046 between 2,770 and 2,780 m of elevation (Figure 14).

Since the probability density functions follow a normal distribution, the second and third quartiles of the White River NF probability density function of lightning-caused fires occurring in areas with mountain pine beetle-caused mortality (1981-1987) fell between 2600 and 2900 m of elevation (Table 8). Total second and third probability quartile hectares in lodgepole pine dominated stands was 14,556 with the probability density function range of a lightning fire and mountain pine beetle-caused mortality areas (1981-1987) co-occurring between 0.0012 and 0.00175. The mode of the White River NF probability density function was 0.0019 (Figure 15).

4.9 Drought indices and fire frequency

No relationships were observed between the Modified Palmer Drought Severity Index and fire frequency via directional chi square test statistics (Table B9). The 1981 fire frequency cell chi square for Arapaho NF ignitions within areas of mountain pine beetle-caused mortality in lodgepole pine was significantly greater than expected. Trends in annual chi squares and drought indices for both NFs over the span of mountain pine beetle -initiation for the White River NF (1980-2003) and the Arapaho NF (1980-2005) had no overall correlation. However, in 1981 there was a positive correlation with Arapaho NF fire frequency and the minimum PMDI in Region 24 and 25 (Figures 16, 17, 18, and 19).

Discussion

We were successful in determining if there was a relationship between fires subsequent to mountain pine beetle outbreaks in lodgepole pine. Using a spatiotemporal, landscape scale approach to fire occurrence from the onset of multiple 1980's mountain pine beetle outbreaks in central Colorado, we found no relationship between areas of mountain pine beetle-caused mortality (non-buffered and 50 m buffered) and subsequent lightning-fire occurrence. However, there were more human and lightning fires combined in the mountain pine beetle areas of the White River NF. This relationship indicated we should explore the spatial locations of fires, mountain pine beetle-caused mortality areas, and meteorological conditions related to the relationships.

We used landscape level data and field assessment to derive our initial findings. Traditional beliefs would indicate we should have seen an increase in fire ignitions or bigger fires in areas with mountain pine beetle-caused mortality (Hopkins 1909, Brown 1975, Parker and Stipe 1993, Arno 2000). The potential factors involved in the relationship between fire frequency and mountain pine beetle-caused mortality involve the meteorological conditions since the outbreak, the frequency of ignitions, the quantity of dead trees in the forest, and forest management and fire suppression activities in the study area. Thus our second objective was to determine if fire frequency subsequent to mountain pine beetle-caused lodgepole pine mortality was related to topographic attributes, fire ignition type, and meteorological conditions.

Modeling biological interactions, such as outbreak mountain pine beetle-caused mortality and fire occurrence, is highly complex. We modeled the probability of lightning-caused fires occurring after mountain pine beetle-caused lodgepole pine mortality based on elevation. It is well known that the incidence of mountain pine beetle attack is influenced by stand structure characteristics, geographic site variables (available moisture, humidity, solar radiation, wind) and within stand temporal microclimate conditions which were unaccounted for in this study. We incorporated a regional scale weather analysis with temporal occurrence of fire frequency and found no statistical correlation between the annual frequency of fires after mountain pine beetle and drought indices.

While the return rate of lodgepole pine type fires within areas of previous mountain pine beetle could be confounded with the fire intensity and extent of any previous fire, our results found there to be only five fires greater than 4 ha spanning 26 years on the Arapaho NF (1980-2005) and 24 years on the White River NF (1980-2003). No fires, human or lightning-caused, within the mountain pine beetle-caused lodgepole pine mortality areas on the Arapaho NF and White River NF were greater than 4 ha. The results suggest not only that there were no differences in lightning-caused fire frequency in and out of mountain pine beetle activity areas on the Arapaho NF and White River NF, but the extent to which these small fires burned in previous mountain pine beetle-caused mortality areas was minimal. The outcome of fire suppression efforts for at least the past three decades across both National Forests is largely unknown. The low frequency of fire occurrence (human or lightning-caused) and the preponderance of recorded small, low severity lodgepole pine type fires occurring where previous mountain pine beetle-caused mortality occurred indicates a weak relationship between mountain pine beetle-caused areas and fire occurrence.

Fire occurrence on the Arapaho NF in mountain pine beetle-caused lodgepole pine mortality areas was not significantly greater for combined human and lightning-caused fires than occurrences outside of the mortality areas. To quantify the spatial error associated with aerial survey techniques, Johnson and Ross (2008) buffered damage agent-caused tree mortality polygons by 50 m which gained 10% in overall accuracy of observed mountain pine beetle damage in lodgepole pine. For the landscape scale approach used in our analysis, buffering the mortality by 50 m increased the affected area by 2,307 ha and 6,088 ha on the Arapaho NF and White River NF, respectively. However, Johnson and Ross (2008) found an additional 7 % increase over the 10% found in their 50 m buffer (overall accuracy =87%) by expanding each lodgepole pine mortality polygon by 500 m. Applying a 500 m buffer to the 1980's observed mortality polygons increased the total aggregated area on the Arapaho NF and White River NF by 24,740 ha and 58,880 ha, respectively.

The White River NF experienced fire occurrences greater than expected across all categories (non-buffered, 50 m buffered and 500 m buffered mortality areas) when considering human and lightning-ignitions combined, however that significance was no longer detected with lightning-caused ignitions in the non-buffered and 50 m buffered mortality categories. Interestingly, across both National Forests human-caused fires accounted for the majority of all ignitions (total 71.7%; Arapaho NF: 71.4 %; White River NF: 71.9%). We do not know why human and lightning-caused fires are related to mountain pine beetle-caused mortality areas on the White River NF, especially since there was no relationship with the variable of nearest roads. Our fire density analysis was limited to the area affected by the mountain pine beetle determined from the air, however the inadequate knowledge of mountain pine beetle-caused mortality intensity and the spatial continuity of mortality intensity within the polygons were unaccounted for.

There were no differences in lightning-fire frequency between areas of previous mountain pine beetle and areas without mountain pine beetle-caused mortality on the Arapaho NF. When only considering lightning fires, there were more observed White River NF fire frequencies than expected in the 500 m buffer analysis. The White River non-buffered and 50 m buffered mortality areas had no difference in fire occurrence in ignitions that occurred within previous mountain pine beetle mortality areas and ignitions that occurred outside of the reported mountain pine beetle-caused mortality. These findings suggest there should be a low priority for management objectives to address landscape scale fire hazards resulting from the 1980's mountain pine beetle on the Arapaho NF and White River NF. Fuel breaks and defensible space should be considered in areas where infrastructure, personal property or safety are of highest concern. Focusing on landscape-scale treatment of forest lands outside of the areas with highest risk to infrastructure, personal property or personal safety, with the objective to mitigate wildland fire occurrence from 1980's mountain pine beetle activity, should be of low consideration. Public education and awareness of the relationship between human-caused fires and mountain pine beetle-caused mortality should be a management focus.

The field assessment resulted in a low frequency of locating fuels from the 1980's mountain pine beetle outbreak. At the time of assessment, error rates of aerial survey data were unknown. The intensity of the 1980's outbreaks is not well known except for the mortality estimates observed from the air and the stand inventory data, and no specific ground attempts to investigate mortality intensity associated with aerial survey data were conducted. Incorporating a 500 m buffer (Johnson and Ross 2008) to the aerial survey data prior to the field assessment of fires and mountain pine beetle-caused mortality may have led to a higher success rate of locating fuels from the 1980's mountain pine beetle outbreaks. Due to the lack of ground sampling data specific to the areas from the 1980's mountain pine beetle outbreaks on both National Forests, the probability of finding contiguous mountain pine beetle-caused mortality remnant coarse woody debris is unknown. As a result of the lack of highly aggregated, contiguous mortality, likely due to the lower intensity of the outbreaks, the field assessment showed little evidence of fire occurrence with mountain pine beetle-caused lodgepole pine mortality. We found 3.8 % of the assessed fires had mountain pine beetle-caused mortality fuels present prior to the ignition. The field assessment further supports a lack of correlation between 1980's mountain pine beetle-caused lodgepole pine mortality and subsequent fire occurrence. The occurrence of the 1980's outbreak in relation to towns and private property or ease of accessibility to fuel wood cutting are likely to influence the level of sanitation and mountain pine beetle-caused mortality tree removal, further altering the hazard and risk of mountain pine beetle-caused mortality-fire interactions.

Cole and Cahill (1976) report an expected 5 to 7 year duration of sustained loss in the Rocky Mountains (Hot Sulpur Springs, CO) from early (1960's) mountain pine beetle epidemics. During the 1960's and 1970's outbreaks near Hot Sulphur Springs, CO and Granby, CO, Cole and Cahill (1976) report losses of just over 10 trees/ha. The average standing mortality, derived from stand inventory data (1978 -1993) across areas with aerially detected mountain pine beetle-caused mortality was consistent (68.4 to 68.9 trees/ha) for the Arapaho and White River NFs. Our findings suggest a 5 to 7 year temporal framework was still the case in the 1980's outbreak on the Arapaho NF and White River NF, since these outbreaks lasted less than 7 years. From our stand inventory analysis, we found six times greater standing mortality during the 1980's outbreak than Cole and Cahill (1976) found in the early 1970's. Klutsch et al. (2009) report 349.5 trees/ha (42%) mortality from the current epidemic mountain pine beetle populations, which encompasses a much greater geographic extent and intensity from 2000 to 2008, which equates to more than 5 times greater tree mortality/ha than that of the 1980's outbreak.

The intensity of the current outbreak in 2008 (more than 71% of the lodgepole pine basal area within the Arapaho NF (Klutsch et al. 2009)) is greater than the 1980's outbreaks (Figures 8, 20). Current epidemic-caused lodgepole pine mortality can increase surface fuel loads and alter the residual stand structure. Larger diameter trees are preferred by the mountain pine beetle (Cole and Amman 1969; Amman et al 1977; Fettig et al. 2007; Klutsch et al 2009), altering the forest structure via large diameter size class reduction, which in turn results in an increase of ladder fuels by releasing the understory. However, in Yellowstone National Park, Renkin and Despain (1992) found fewer than expected fire occurrences and activity in the successional lodgepole pine forests, compared to fire occurrences in mixed Engelmann spruce-lodgepole pine type stands. This suggests the remaining forest characteristics after a mountain pine beetle outbreak could have fewer fire occurrences simply based on structure or successional stage. Further research is needed to identify how the live and dead fuel structure in these twenty year or older mountain pine beetle-affected forests will be altered over decades.

The independent spatial relationship of where mountain pine beetle outbreaks are likely to occur and where lightning fires might occur based on elevation is inherently variable due to topographic and forest characteristic variation. The probability of randomly locating a 0.003 ha area on a given forest that is likely to have mortality from a seven to eight year long 1980's mountain pine beetle outbreak and a lightning fire occurrence is low. However, through our comparative spatial analysis of the Arapaho NF and White River NF, the maximum probability density function of both a lightning fire and a 1980's mountain pine beetle-caused mortality area occurring was greatest on the Arapaho NF. The combined lodgepole pine area of the second and third probability density quartiles was similar between forests. Due to orthogeographic variability between National Forests, locating elevations of highest probability where 1980's mountain pine beetle-caused mortality, lightning fires prior to 1980, and the occurrence of lightning fires post-1980 within mountain pine beetle polygons on each National Forest independently furthers our knowledge in identifying where on the landscape the hazards and risks are greatest for co-occurrence. As the current epidemic grows in spatial extent and intensity, the spatial analysis could and should be expanded to include recent epidemic mountain pine beetle-caused mortality.

Our overlay analysis of directional cell chi square values and Modified Palmer Drought Severity Indices (PMDI) found no significant relationship for any given year, excluding 1981 on the Arapaho NF. Since the outbreak on the Arapaho NF was in the incipient phase in 1981, the significance of the cell chi square value for 1981 is likely not due to the mountain pine beetle-caused lodgepole pine mortality. Extreme drought was observed for Colorado Region 24 and Region 25 in 1981 (Colorado Climate Center) and likely the result of the significant cell chi square value. Previous work based on fire-scar records from 1700 to 1920 found a positive relationship of fire incidence and occurrence with drought years in the upper montane forests (Sherriff and Veblen 2008). Contrary to previous findings of drought indices and fire occurrence relationships, our results suggest there was no relationship with fire occurrence and prolonged drought years after the 1980's outbreak of mountain pine beetle on the Arapaho NF and White River NF. However, our analysis was based on much shorter temporal scales and different fire sizes than previously reported (Schoennagel et al. 2007, Sibold et al. 2006)

Bessie and Johnson's (1995) findings support the hypothesis that greater fire behavior and fire extent are associated with extreme meteorological years rather than fuel accumulation/load. However, intensity and extent of a fire event are indices used to assess the fire severity once an ignition spreads but they do not address whether aerial and surface fuel alterations (mountain pine beetle-caused mortality areas) are likely to sustain a higher frequency of subsequent ignitions making them focal areas of wildland fire. Our findings suggest that areas on the Arapaho NF and White River NF having experienced an outbreak of mountain pine beetle-caused mortality have no significant difference in fire frequency post-outbreak. Due to long-term alterations in stand characteristics (crown density, competition, increases in solar radiation, microclimate) live grass (grass height; Klutsch 2009), forbs and shrub production are increased (Page and Jenkins (2007b). However, the interactions between increases in live understory production resulting from a mountain pine beetle outbreak in lodgepole pine and subsequent fire occurrence are unknown. There has been considerable debate regarding an increase in herbaceous understory leading to a reduction in fire occurrence due to higher fine fuel moisture content in the herbaceous understory. However, seasonal drought conditions coupled with late season timing of an ignition source in mountain pine beetle stands with altered fuel complexes could have a localized effect on overall fire frequency if the herbaceous layer has cured.

Seasonal time-lag analyses that identify cool, higher precipitation periods followed by dry, warm periods have shown a positive correlation in fire incidence and subsequent warm dry phases (Swetnam and Betancourt 1998). However, Bessie and Johnson's (1998) findings were in dry, low elevation forests dominated by grass surface fuel, and the applicability of this type of analysis is unknown in Colorado lodgepole pine forests. On the landscape scale, regional fire years were positively correlated with specific El Nino Southern Oscillation (ENSO), Pacific Decadal Oscillation and Atlantic Multidecadal Oscillations (AMO) (Kitzberger et al. 2001; Schoennagel et al. 2005; Schoennagel et al. 2007; Sheriff and Veblen 2008). An expanded meteorological analysis including multi-annual time-lags and continental oscillations could build on the results of this study to assess further where and when fire occurrences are likely in reference to mountain pine beetle outbreaks/epidemics; however, we are limited by a lack of large fires in these two National Forests.

Conclusions

Our study found no relationship between lightning-caused fires and areas of previous moderate severity outbreak mountain pine beetle-caused lodgepole pine mortality on the Arapaho NF and White River NF. Human and lightning-caused fire occurrences were significantly greater than the expected fire occurrence on the White River NF, but no significant differences were found on the Arapaho NF. From our logistic modeling of human and lightning-caused fires, elevation is the most significant variable in predicting fire occurrence in areas with 1980's mountain pine beetle-caused mortality on the Arapaho NF and White River NF. The results presented in this study are an attempt to quantify fire occurrence in relation to prior mountain pine beetle-caused lodgepole pine mortality. The variability in fire occurrence and spatial location of mountain pine beetle outbreaks between the Arapaho NF and White River NF tempers extrapolation of the results to other locations.

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Table 1. Chi square tests for independence of fire frequency (human and lightning-caused and lightning only: Arapaho NF:1980-2005; White River NF:1980-2003) and mountain pine beetle-caused mortality (Arapaho NF:1980-1987; White River NF:1981-1987)

Arapaho National Forest		Human and Lightning Fire Frequency		Lightning Fire frequency	
		Buffer (meters)		Buffer (meters)	
		0	50	0	50
	Observed w/ MPB	14	18	7	8
	Observed w/o MPB	249	245	68	67
	Expected Fires MPB	13.3	14.6	3.8	4.2
	Expected Fires W/o MPB	249.7	248.4	71.2	70.8
Area (hectares)[A]					
	Observed w/ MPB	22724.5	25046.6	22724.5	25046.6
	Observed w/o MPB	427798.1	425476.1	427798.1	425476.1
	Critical Value	3.84146		3.84146	
	Degrees of Freedom	1		1	
	Chi 2	0.04280	0.82667	2.88093	3.72595
	P-value	0.83611	0.36324	0.08963	0.05357
White River National Forest		Buffer (meters)		Buffer (meters)	
		0	50	0	50
	Observed w/ MPB	43	49	6	9
	Observed w/o MPB	160	154	50	47
	Expected Fires MPB	17.5	19.0	4.8	5.2
	Expected Fires W/o MPB	183.5	184.0	51.2	50.8
Area (hectares)[A]					
	Observed w/ MPB	71909.1	77997.9	71909.1	77997.9
	Observed w/o MPB	761962.1	755873.4	761962.1	755873.4
	Critical Value	3.84146		3.84146	
	Degrees of Freedom	1		1	
	Chi 2	40.14808	52.33104	0.31065	2.98056
	P-value	2.3542E-10	4.6896E-13	0.5773	0.0843

[A]hectares with/without USDA Forest Service Aerial Detection Survey mountain pine beetle-caused mortality

Table 2. Parameter estimates from Logistic regression model predicting the presence of mountain pine beetle-caused lodgepole pine mortality with fire on the Arapaho National Forest and White River National Forest, CO.

Parameter	DF	Estimate	SE[1]	p[2]	95% C.I	
Intercept	1	-58.7959	30.2588	0.052	-118.1	0.5103
Elevation (meters)	1	0.0462	0.0214	0.0311	0.00419	0.0883
Elevation quadratic term	1	0.0000092	0.000003804	0.0156	-0.00002	-0.00000175
Forest (Arapaho; White River)	1	10.1155	3.8889	0.0093	2.4933	17.7376
Elevation Forest Interaction term	1	-0.00394	0.00141	0.0051	-0.00669	-0.00118

[1] Standard error of the parameter estimate

[2] P-value based on Wald Chi-Square Statisitic

Table 3. Arapaho National Forest fire sizes (1980-2005) within and outside areas with aerially detected mountain pine beetle-caused mortality (1980-1987).

Forest and MPB intersection[A]	Reported Hectares	Frequency	Percent	Cumulative Frequency	Cumulative Percent
Arapaho NF without MPB	0	51	20.5	51	20.5
	0.04	155	62.3	206	82.7
	0.08	9	3.6	215	86.4
	0.12	6	2.4	221	88.8
	0.16	1	0.4	222	89.2
	0.20	5	2.0	227	91.2
	0.28	2	0.8	229	92.0
	0.32	1	0.4	230	92.4
	0.40	6	2.4	236	94.8
	0.53	1	0.4	237	95.2
	0.61	2	0.8	239	96.0
	0.69	1	0.4	240	96.4
	0.81	1	0.4	241	96.8
	1	1	0.4	242	97.2
	2	2	0.8	244	98.0
	2	2	0.8	246	98.8
	5	1	0.4	247	99.2
	193	1	0.4	248	99.6
	196	1	0.4	249	100.0
Arapaho NF with MPB	0.04	11	78.6	11	78.6
	0.08	1	7.1	12	85.7
	1	1	7.1	13	92.9
	4	1	7.1	14	100.0

[A] National Forest and the fire occurrence with/without intersection of MPB-caused mortality polygons

Table 4. White River National Forest fire sizes (1980-2003) within and outside areas with aerially detected mountain pine beetle-caused mortality (1981-1987).

Forest and MPB intersection[A]	Reported Hectares	Frequency	Percent	Cumulative Frequency	Cumulative Percent
White River NFwithout MPB	0	67	41.9	67	41.9
	0.04	62	38.8	129	80.6
	0.08	8	5.0	137	85.6
	0.12	9	5.6	146	91.3
	0.20	5	3.1	151	94.4
	0.81	2	1.3	153	95.6
	1	1	0.6	154	96.3
	1	2	1.3	156	97.5
	2	1	0.6	157	98.1
	4	1	0.6	158	98.8
	11	1	0.6	159	99.4
	270	1	0.6	160	100.0
White River NF with MPB	0	19	44.2	19	44.2
	0.04	13	30.2	32	74.4
	0.12	2	4.7	34	79.1
	0.20	6	14.0	40	93.0
	0.28	1	2.3	41	95.4
	0.81	1	2.3	42	97.7
	1	1	2.3	43	100.0

[A] National Forest and the fire occurrence with/without MPB-caused mortality polygons

Table 5. Tree density on stand inventory plots in stands having 20% or greater lodgepole pine basal area, Arapaho and White River National Forest (1978-1993). Trees included diameters greater than 12.7 centimeters at breast height.

Arapaho NF	Status[A]	MPB[B]	TPA[C]	SD[D] (ac)	SE[E]	Range[F] (ac)	TPH[G]	SD (ha)	Range (ha)	N[H]
All plots	Live standing	No	299.4	151.5	2.87	0 - 1086.2	739.8	374.4	0 - 2684.1	2789
	Dead Standing	No	25.6	37.9	0.717	0 - 289.1	63.3	93.7	0 -714.4	2789
	Live standing	Yes	286.6	132.9	4.47	0 - 1573.7	708.2	328.4	0 - 3888.8	885
	Dead Standing	Yes	27.7	38.2	1.28	0 - 372.5	68.4	94.4	0 - 920.4	885
Lodgepole only*	Live standing	No	246	157.5	2.99	0 - 1086.2	607.9	389.2	0 - 2684.1	2772
	Dead Standing	No	19.5	32.1	0.61	0 -275.7	48.2	79.3	0 - 681.3	2772
	Live standing	Yes	251.9	138.6	4.66	0 - 1494.5	622.5	342.5	0 - 3693.1	885
	Dead Standing	Yes	23.7	34	1.14	0 - 372.5	58.6	84.0	0 - 920.4	885
White River NF	Live standing	No	343.7	182.5	4.25	0 - 1301.4	849.3	451.0	0 - 3215.9	1844
All plots	Dead Standing	No	27.1	44.6	1.04	0 - 699.1	67.0	110.2	0 - 1727.6	1844
	Live standing	Yes	358.3	155.1	4.88	0 - 1109.8	885.4	383.3	0 - 2742.5	1009
	Dead Standing	Yes	38	47.9	1.51	0 - 552.8	93.9	118.4	0 - 1366.1	1009
Lodgepole only*	Live standing	No	258.5	191.9	4.47	0 - 1301.4	638.8	474.2	0 - 3215.9	1842
	Dead Standing	No	18.5	37.7	0.878	0 - 699.1	45.7	93.2	0 - 1727.6	1842
	Live standing	Yes	269.3	171.3	5.4	0 - 1109.8	665.5	423.3	0 - 2742.5	1008
	Dead Standing	Yes	27.9	40.8	1.28	0 - 552.8	68.9	100.8	0 - 1366.1	1008

*Inventory records selected on *Pinus contorta species*; Lodgepole pine

[A]Standing tree status of live or dead

[B]Stand gis intersection with aerially detected mountain pine beetle-caused mortality

[C]Stand mean tree per acre equivalence-calculated from plot frequency per stand averaged over all stands

[D]Standard deviation

[E]Standard error of mean stand tree per acre equivalence

[F]Range of mean stand tree per acre equivalence

[G]Mean tree per hectare equivalence

[H]The number of inventoried stands

Table 6. Stand basal area on inventory plots in stands containing 20% or greater lodgepole pine basal area, Arapaho and White River National Forests (1978-1993). Trees included breast height diameters greater than 12.7 centimeters.

Arapaho NF	Status[A]	MPB[B]	BA[C]	Std Dev[D]	SE[E]	Range[F]	N[G]
All plots	Live standing	No	26.52	11.00	0.2080	0 - 68.9	2789
	Dead Standing	No	2.41	3.47	0.0654	0 - 27.6	2789
	Live standing	Yes	23.74	9.83	0.3302	0 - 145.8	885
	Dead Standing	Yes	2.18	2.92	0.0980	0 - 21.4	885
Lodgepole only*	Live standing	No	21.33	10.70	0.2032	0 - 68.9	2772
	Dead Standing	No	1.76	2.66	0.0507	0 -18.4	2772
	Live standing	Yes	20.78	9.48	0.3187	0 - 136.6	885
	Dead Standing	Yes	1.85	2.53	0.0852	0 - 21.4	885
White River NF	Live standing	No	31.23	12.15	0.2826	0 - 82.7	1844
All plots	Dead Standing	No	2.53	3.70	0.0863	0 - 41.3	1844
	Live standing	Yes	34.35	10.49	0.3302	0 -68.9	1009
	Dead Standing	Yes	3.56	4.66	0.1467	0 - 41.3	1009
Lodgepole only*	Live standing	No	23.07	12.54	0.2918	0 - 64.3	1842
	Dead Standing	No	1.70	2.82	0.0659	0 - 41.3	1842
	Live standing	Yes	26.56	12.44	0.3922	0 - 68.9	1008
	Dead Standing	Yes	2.69	4.00	0.1256	0 - 31.2	1008

*Inventory records selected on *Pinus contorta* species; Lodgepole pine

[A]Standing tree status of live or dead

[B]Stands intersecting with ADS mountain pine beetle-caused mortality

[C]Mean basal area equivalence (m^{2}/ha)-calculated from averaged plot frequency per stand averaged over all stands

[D]Standard deviation

[E]The standard error of the mean stand basal area (m^{2}/ha)

[F]The minimum to maximum average stand basal area (m^{2}/ha)

[G]Number of inventoried stands

Table 7. Joint probability surface summary (National Forest area and lodgepole pine cover type area) of probability density function area quartile on the Arapaho and White River National Forests, CO.

Arapaho NF probability quartile areas

Elevations[A]	NF (ha)[B]	Lodgpole (ha)[C]	PDF[D]	Max PDF[E]
<2710	51,340	8,107	0 - .0030	
2710-2760	22,326	6,330	.0031 - .0044	
2761-2815	29,816	10,067	.00441 - .0042	0.0046
>2815	404,467	77,430	.0042 - 0	

White River NF probability quartile areas

Elevations[A]	NF (ha)[B]	Lodgepole (ha)[C]	PDF[D]	Max PDF[E]
<2600	136,130	2,728	0 - .0012	
2600-2760	116,418	5,408	.0012 - .00175	
2761-2900	125,307	9,148	.00175 - .00171	0.0019
>2900	562,327	31,590	.00172 - 0	

[A] Elevation range quartiled (Q1-Q4) of Probability Density Fxn

[B] Hectares of Q1-Q4 across entire NF

[C] Hectares of Q1-Q4 in lodgepole pine dominated stands

[D] Probability Density Fxn range (Q1-Q4) of lightning fire and MPB polygons co-occuring

[E] Maximum Probability Density Fxn of a lightning fire and MPB polygons jointly occuring

Figure 1. *Pinus contorta* species range in Colorado with Arapaho and White River National Forests (Little 1971).

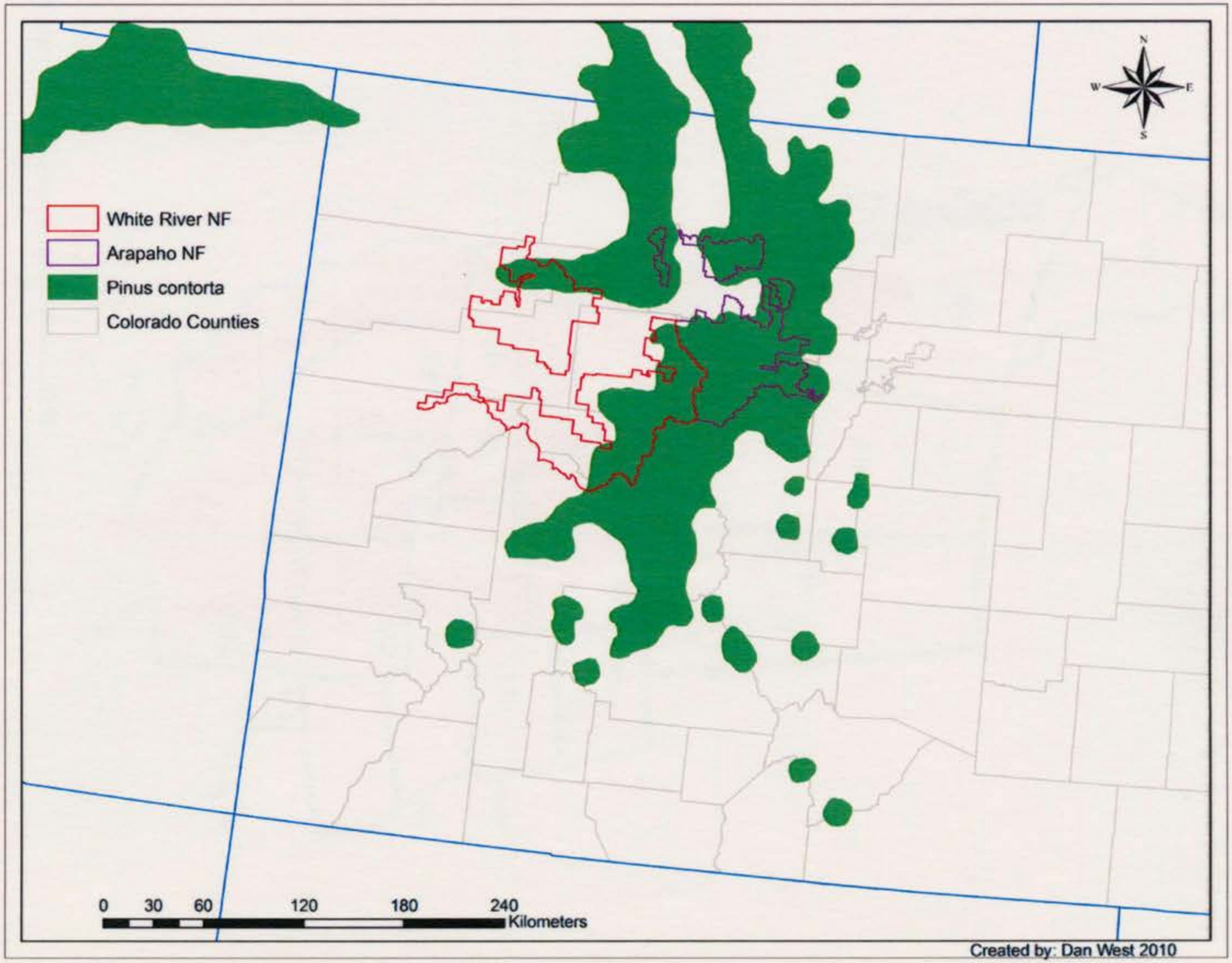

White River NF
Arapaho NF
Pinus contorta
Colorado Counties
N
S
E
W
0 30 60 120 180 240
Kilometers
Created by: Dan West 2010

Figure 2. *Dendroctonus ponderosae* Hopkins (mountain pine beetle) distribution in North America.

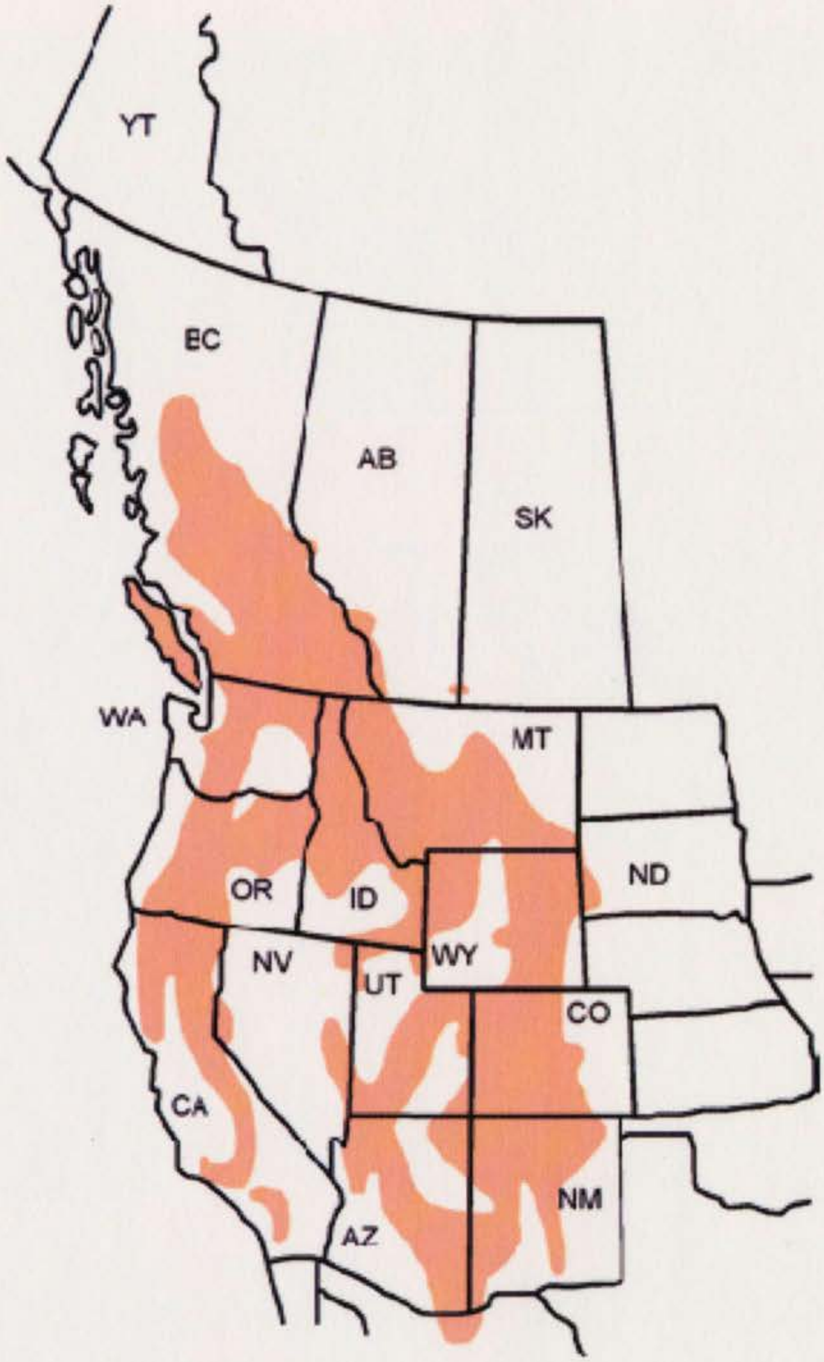
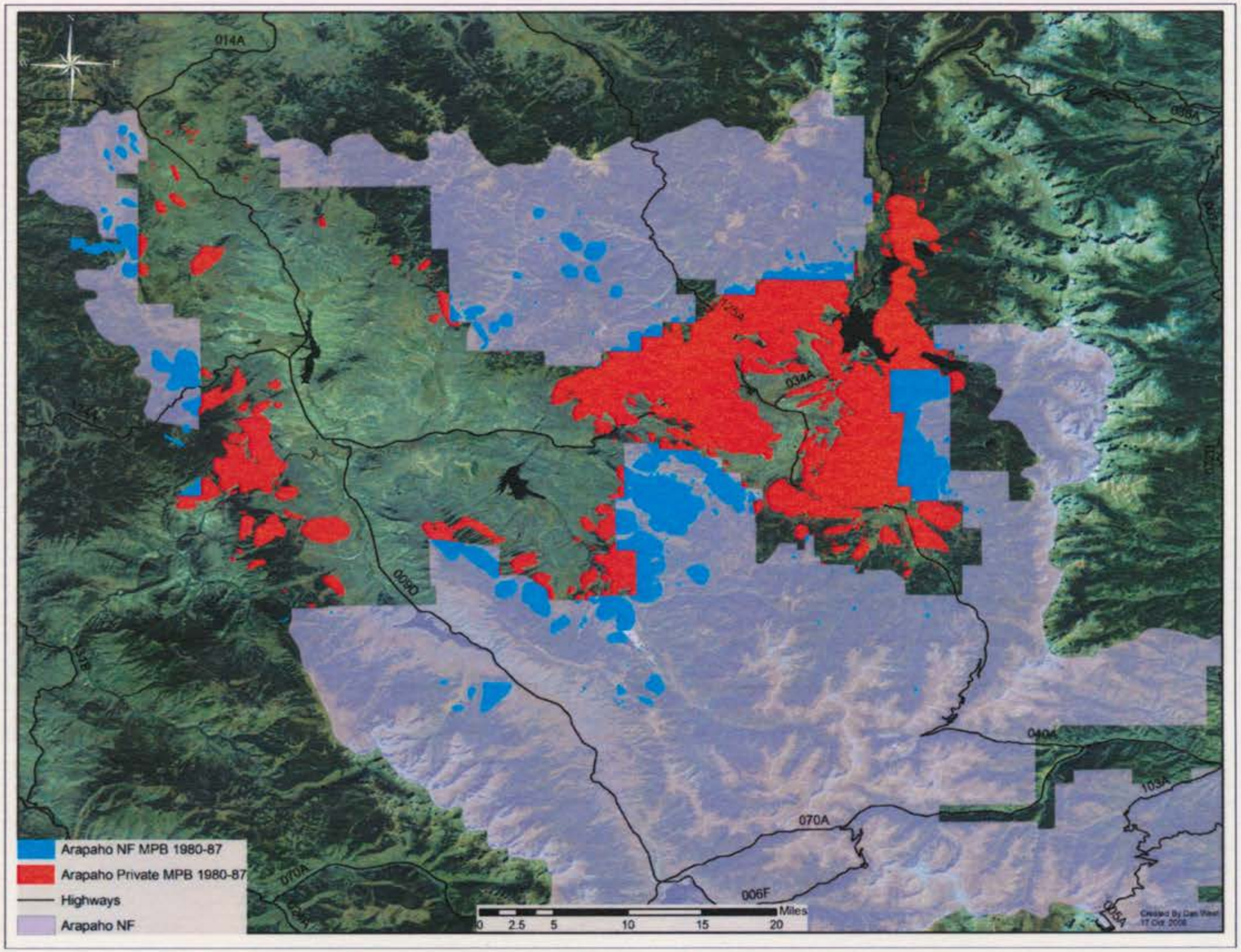


Image from Safranyik and Carroll 2006.

Figure 3. USDA Forest Service, Region 2 Aerial Detection Survey areas of mountain pine beetle-caused mortality (1980-1987) on non-National Forest and Arapaho National Forest, CO.



Arapaho NF MPB 1980-87
Arapaho Private MPB 1980-87
Highways
Arapaho NF
Miles
0 2.5 5 10 15 20
014A
070A
006F
103A
040A
034A
009D

Figure 4. USDA Forest Service, Region 2 Aerial Detection Survey areas of mountain pine beetle-caused mortality (1981-1987) on non-National Forest and White River National Forest, CO.

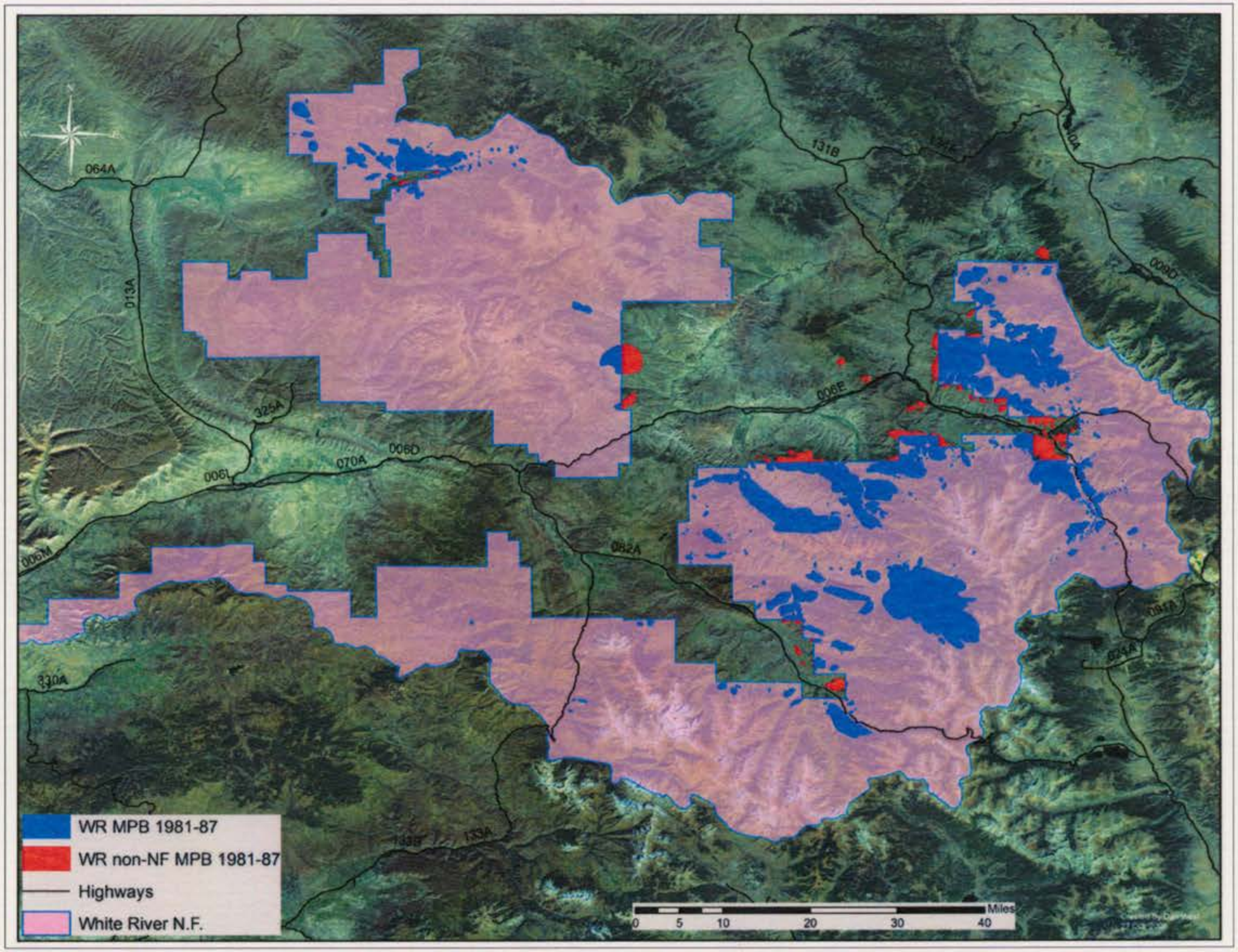

WR MPB 1981-87
WR non-NF MPB 1981-87
Highways
White River N.F.
Miles
0 5 10 20 30 40
064A
013A
325A
006L
070A
006D
006M
082A
131B
006E
009D
024A

Figure 5. Lodgepole pine dominated stands (USDA Forest Service R2Veg species composition $\geq$ 50%) on the Arapaho National Forest, CO.

Arapaho NF lodgepole pine dominated cover type

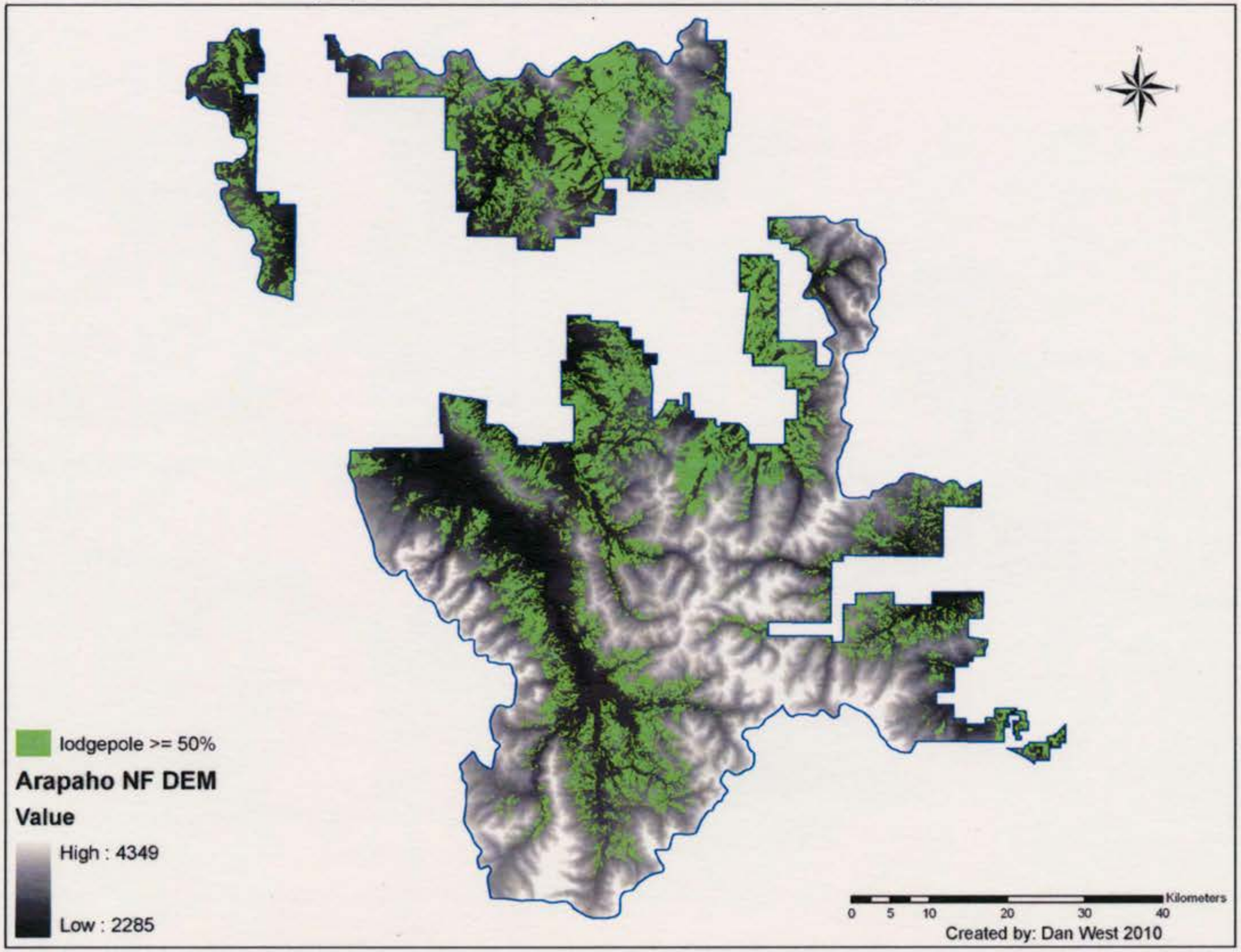


Figure 6. Lodgepole pine dominated stands (USDA Forest Service R2Veg species composition ≥ 50%) on the White River National Forest, CO.

White River NF lodgepole pine dominated cover type

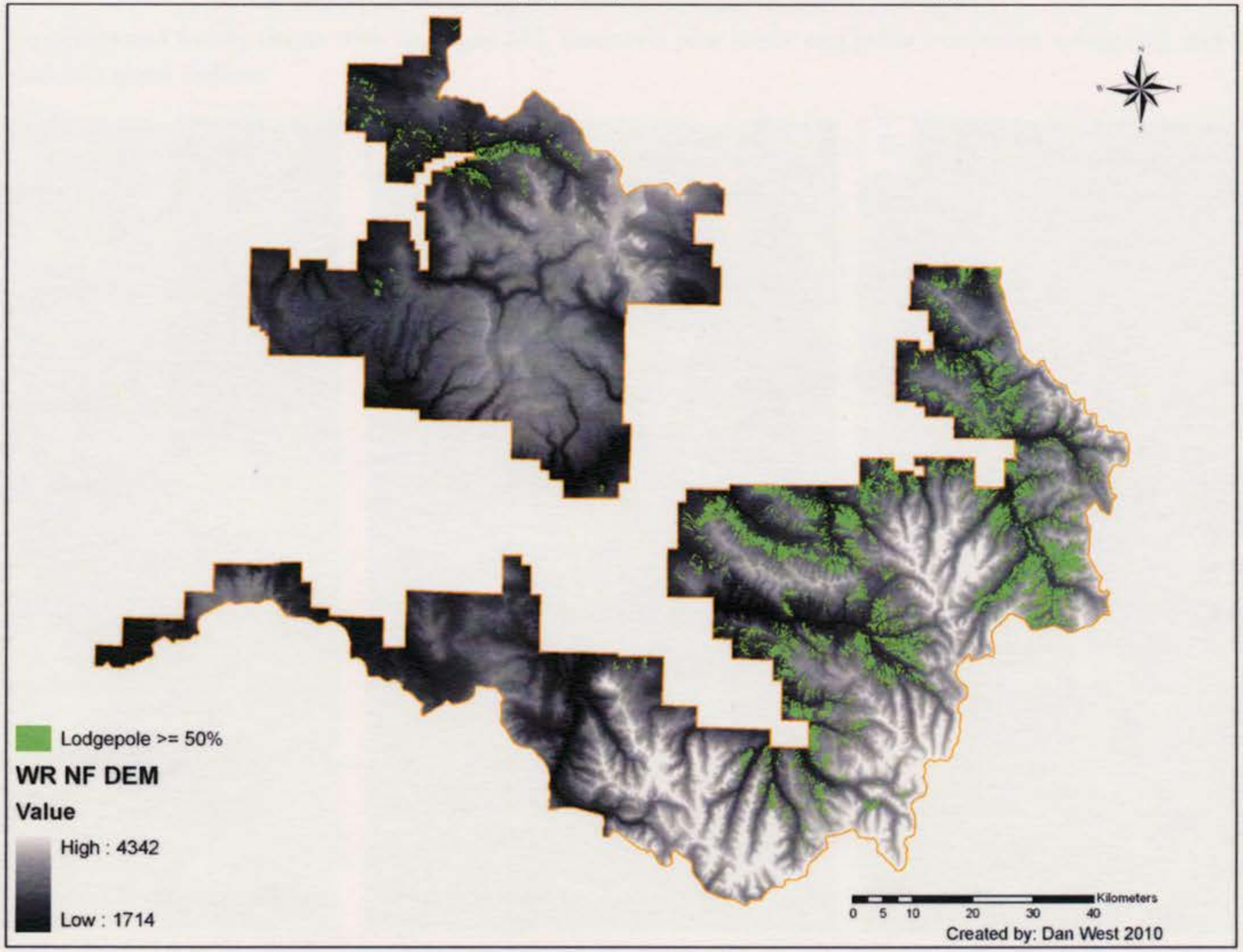


Figure 7. Images of downed woody debris with fire signs (A), mountain pine beetle egg gallery etched in xylem (B), and downed with 50 meter and 500 meter buffers.

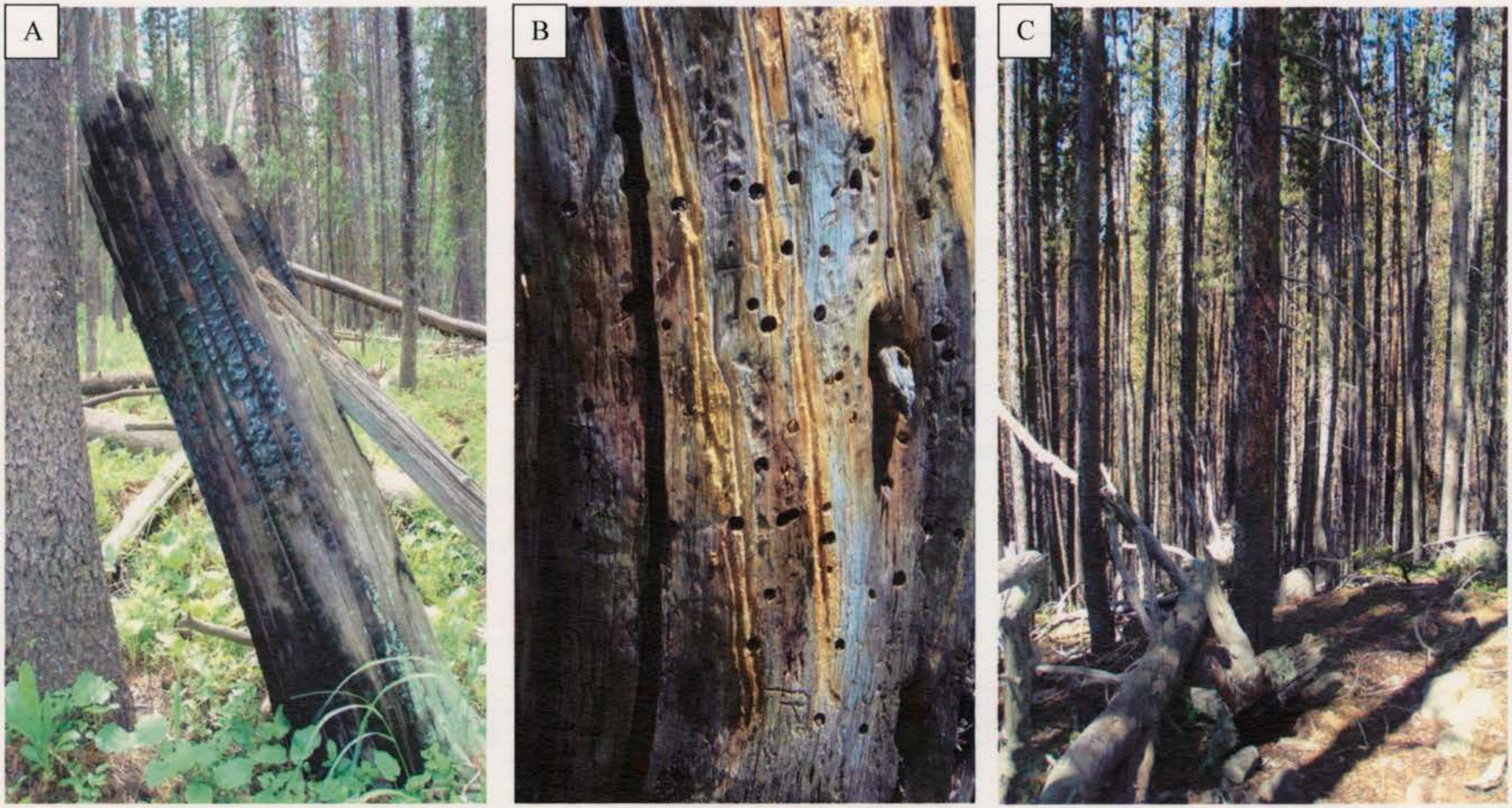


Figure 8. Annual (1980-1987) percent lodgepole pine dominated stands affected by mountain pine beetle (USDA Forest Service Region 2 Aerial Detection Survey): Arapaho National Forest total lodgepole pine area 102,052 hectares; White River National Forest total lodgepole pine area 79,922 hectares.

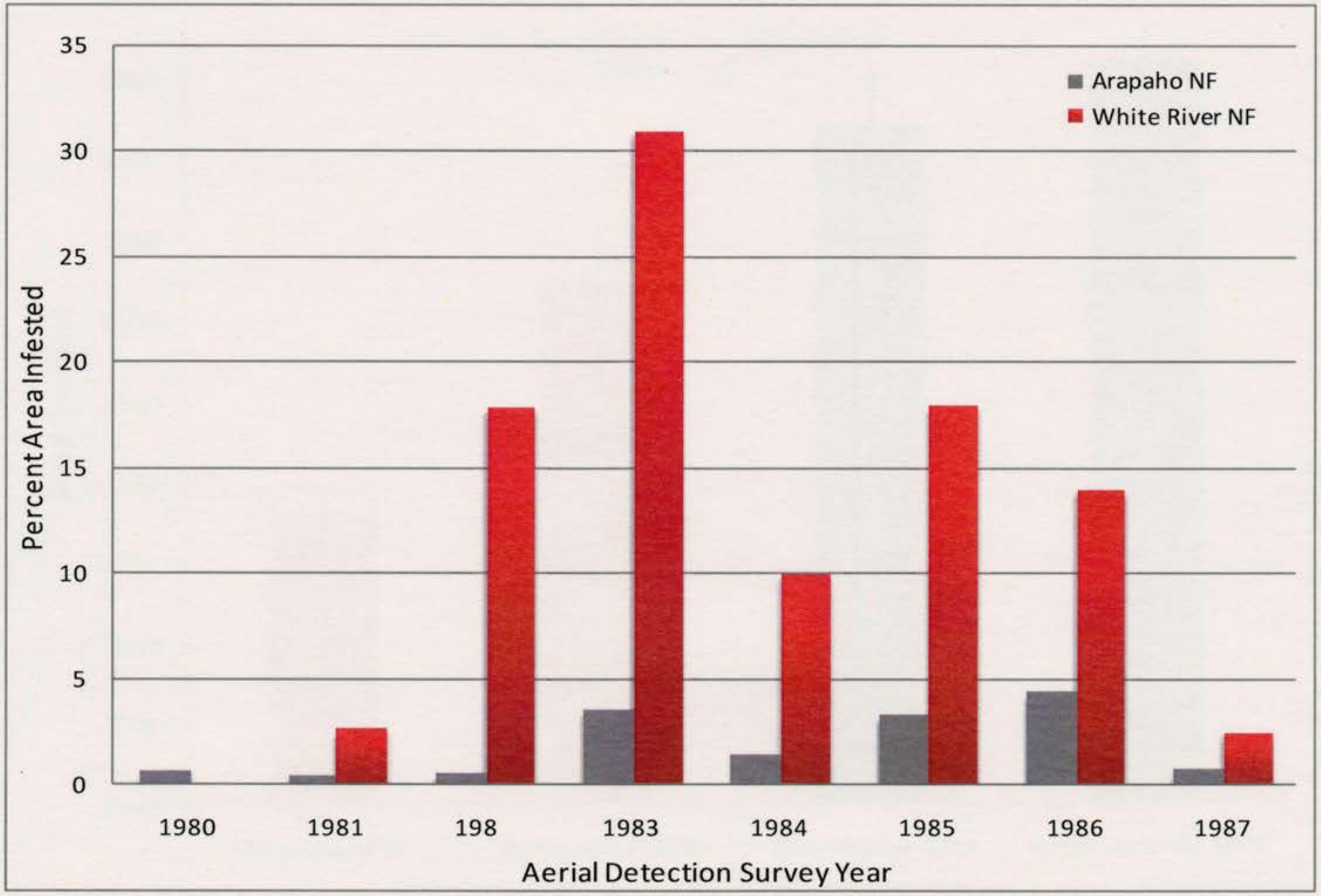


Figure 9. Mean fire (1980-2005) elevations within mountain pine beetle-caused mortality areas on the Arapaho National Forest (1980-1987) and White River National Forest (1981-1987).

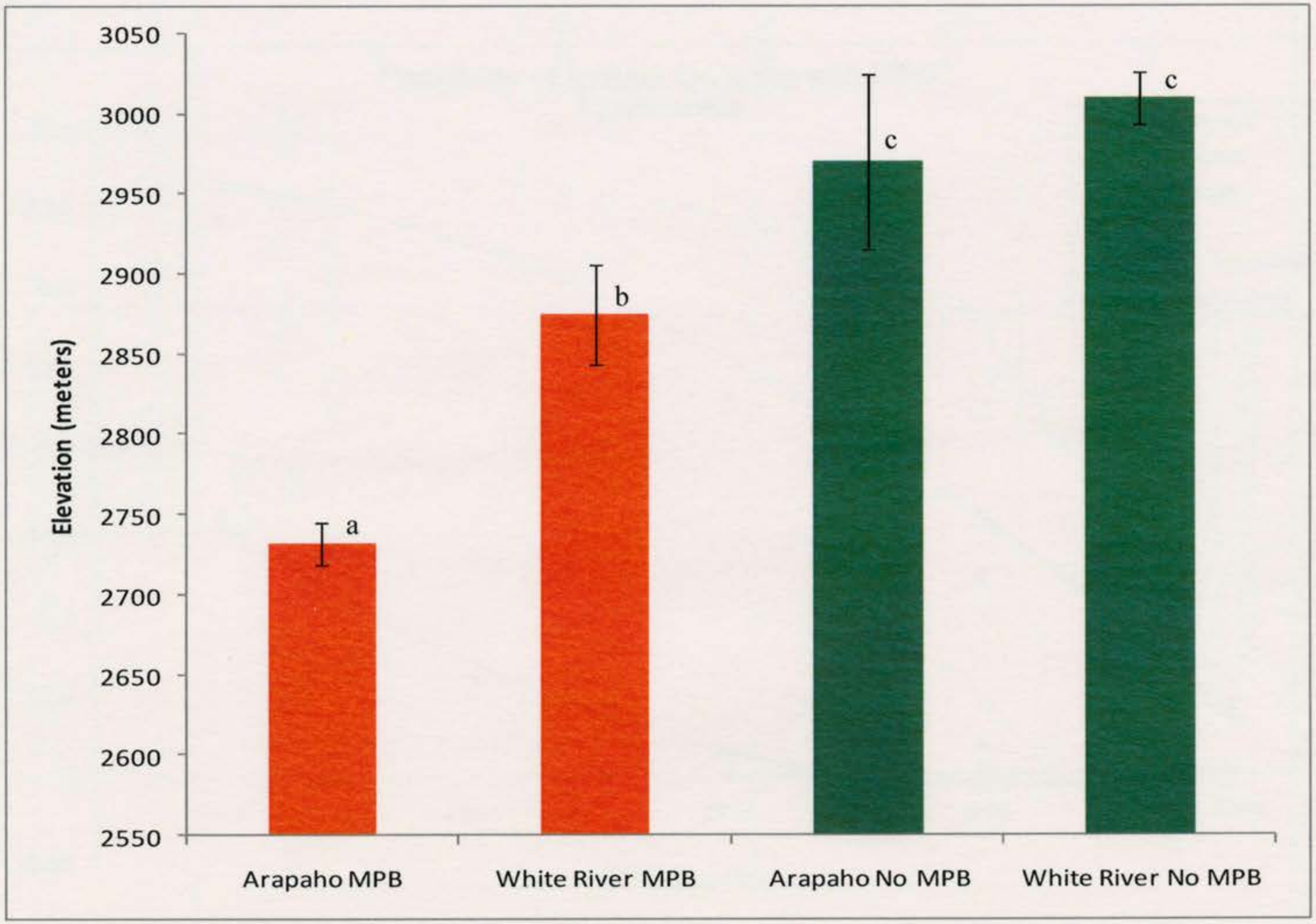


Figure 10. Logistic model of fire occurrence (Arapaho NF: 1980-2005; White River NF: 1980-2003) with mountain pine beetle-caused lodgepole pine mortality areas (Arapaho NF: 1980-87; White River NF: 1981-87) on the Arapaho and White River National Forests, CO.

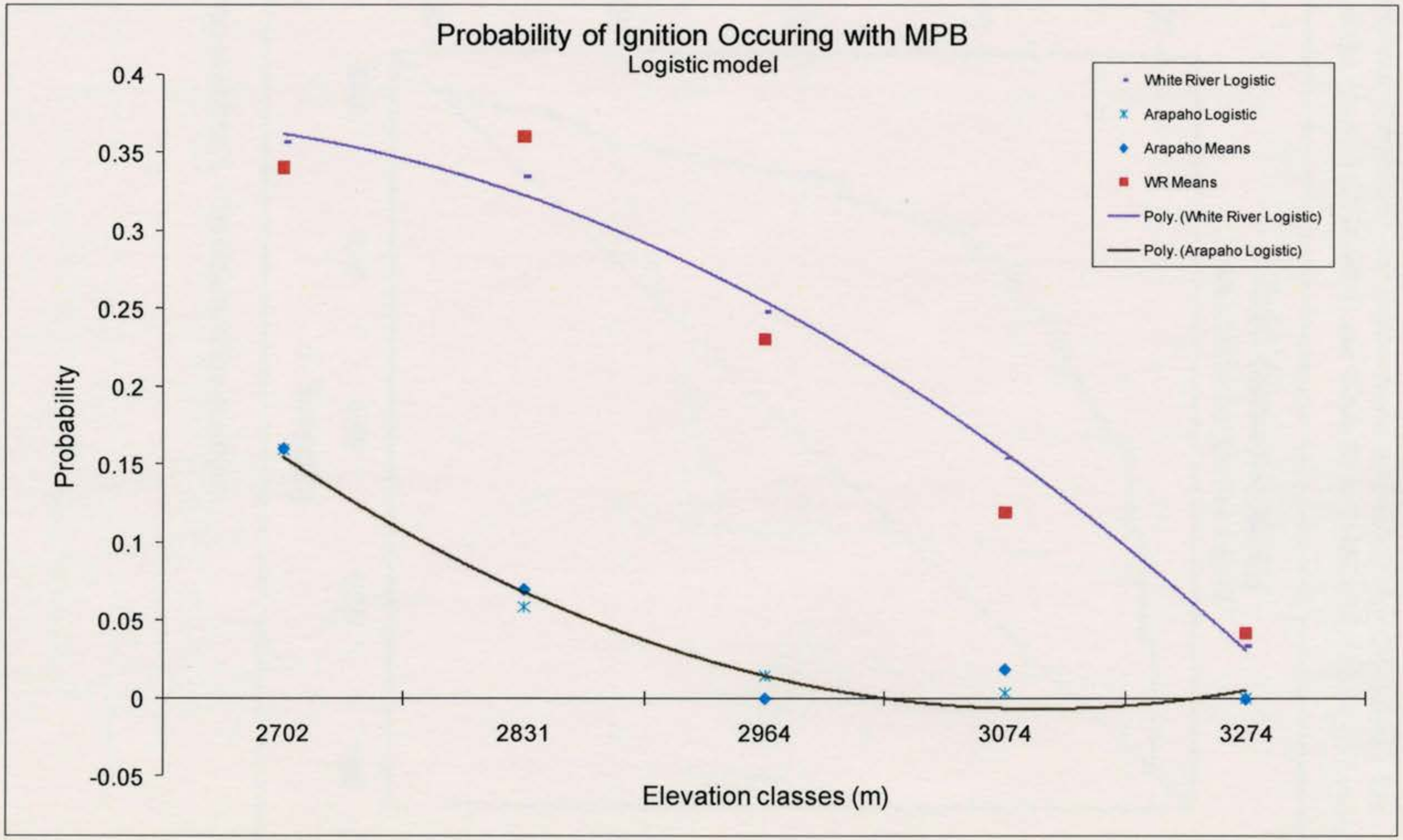
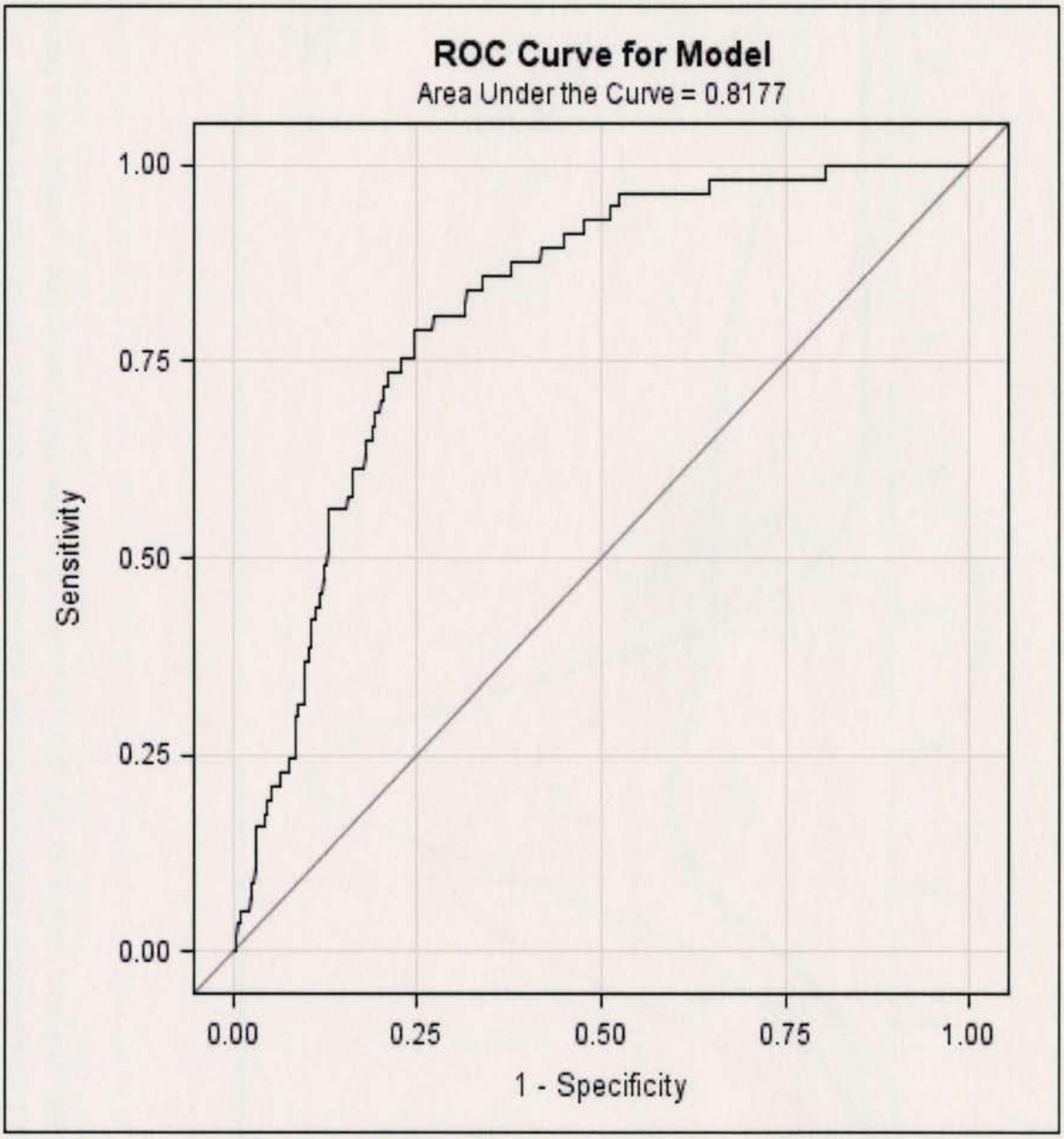


Figure 11. Receiver Operator Characteristic curve for logistic regression model predicting presence of mountain pine beetle-caused mortality (1980-1987) with a fire occurrence on the Arapaho (1980-2005) and White River (1980-2003) National Forests.



Sensitivity=true positives; 1 – Specificity=false positives

Figure 12. Arapaho National Forest elevation probability density functions for mountain pine beetle-caused mortality (MPB), lightning-caused fires pre-1980, and joint occurrence of lightning-caused fires post-1980 intersecting mountain pine beetle-caused mortality.

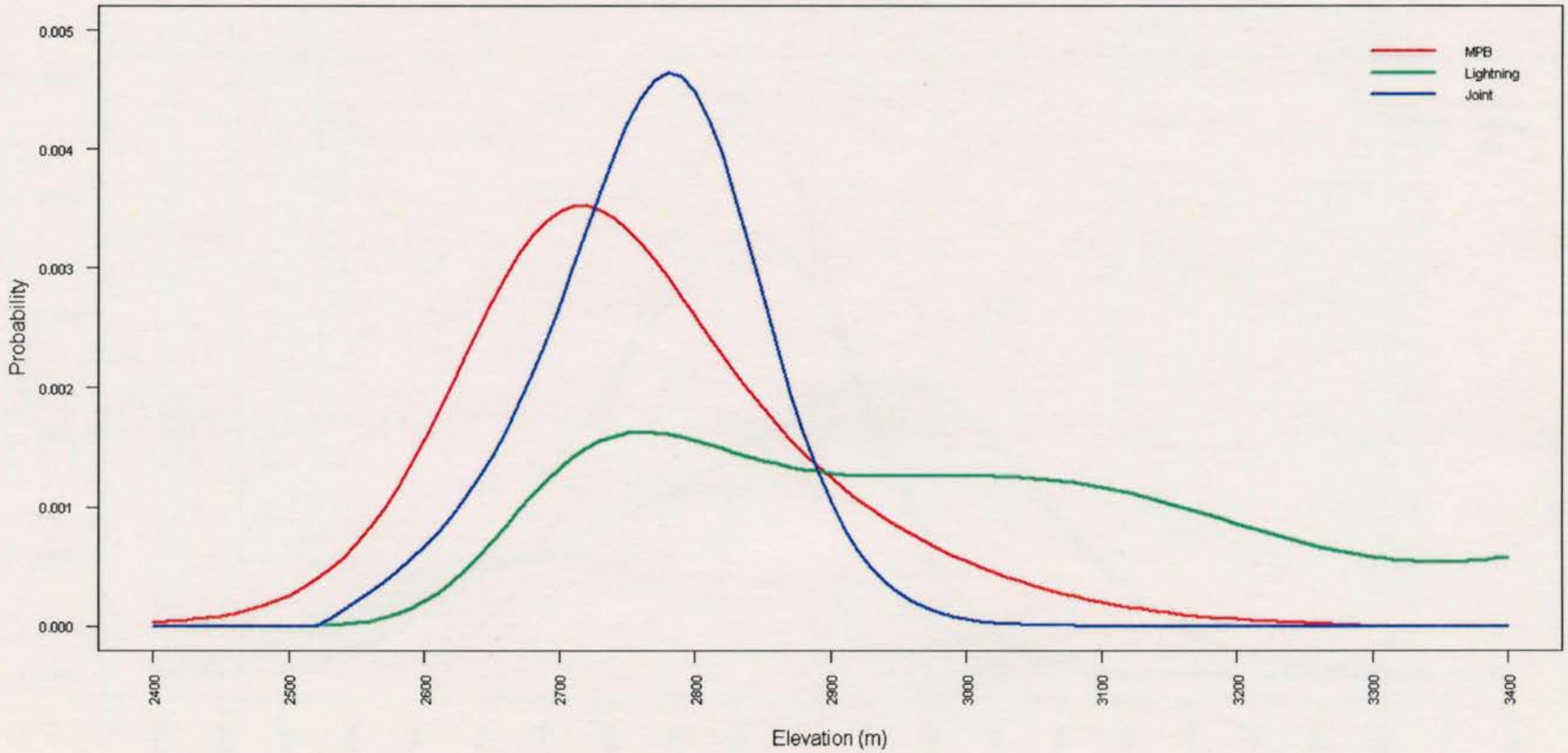


Figure 13. White River National Forest elevation probability density functions for mountain pine beetle-caused mortality (MPB), lightning-caused fires pre-1980, and joint occurrence of lightning-caused fires post-1980 intersecting mountain pine beetle-caused mortality.

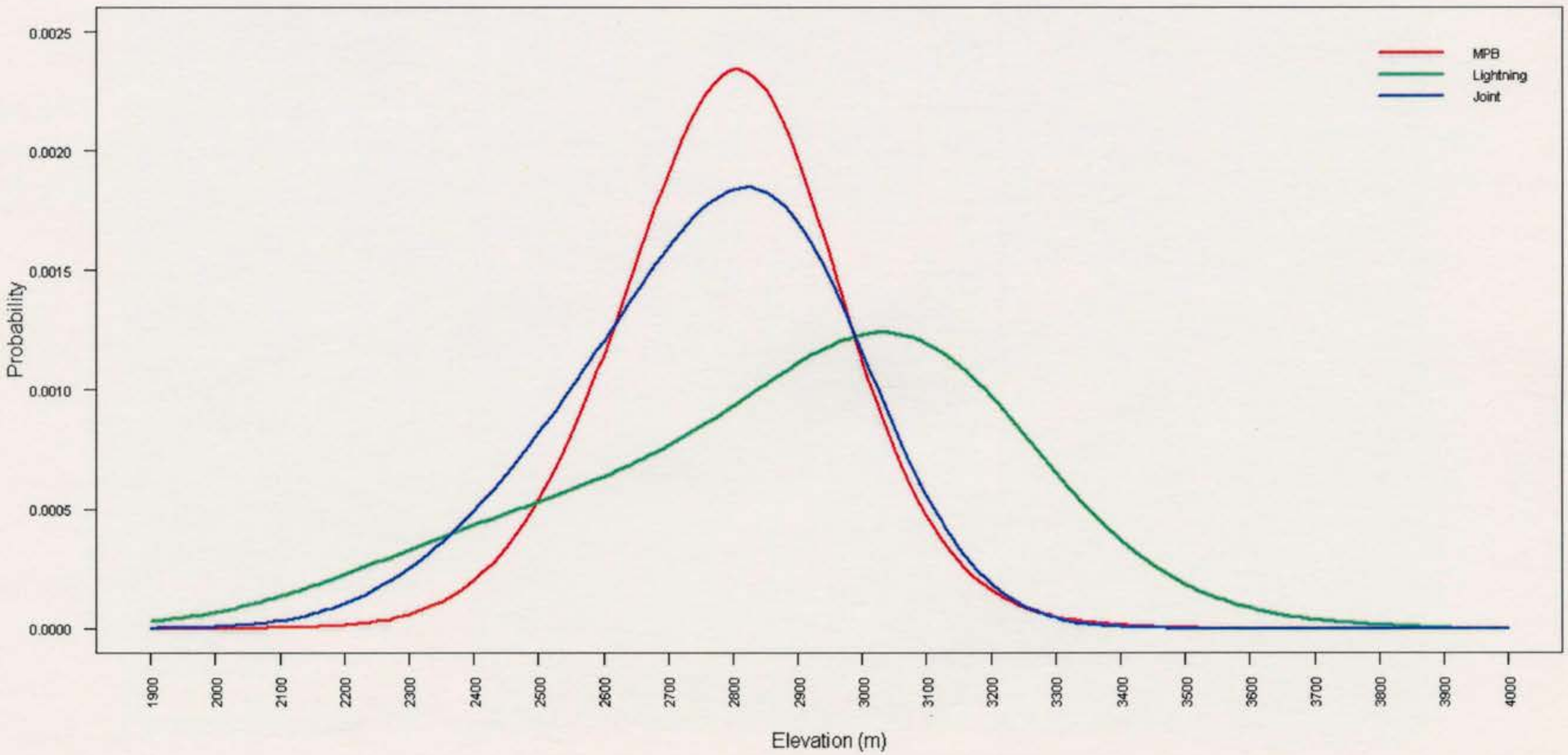
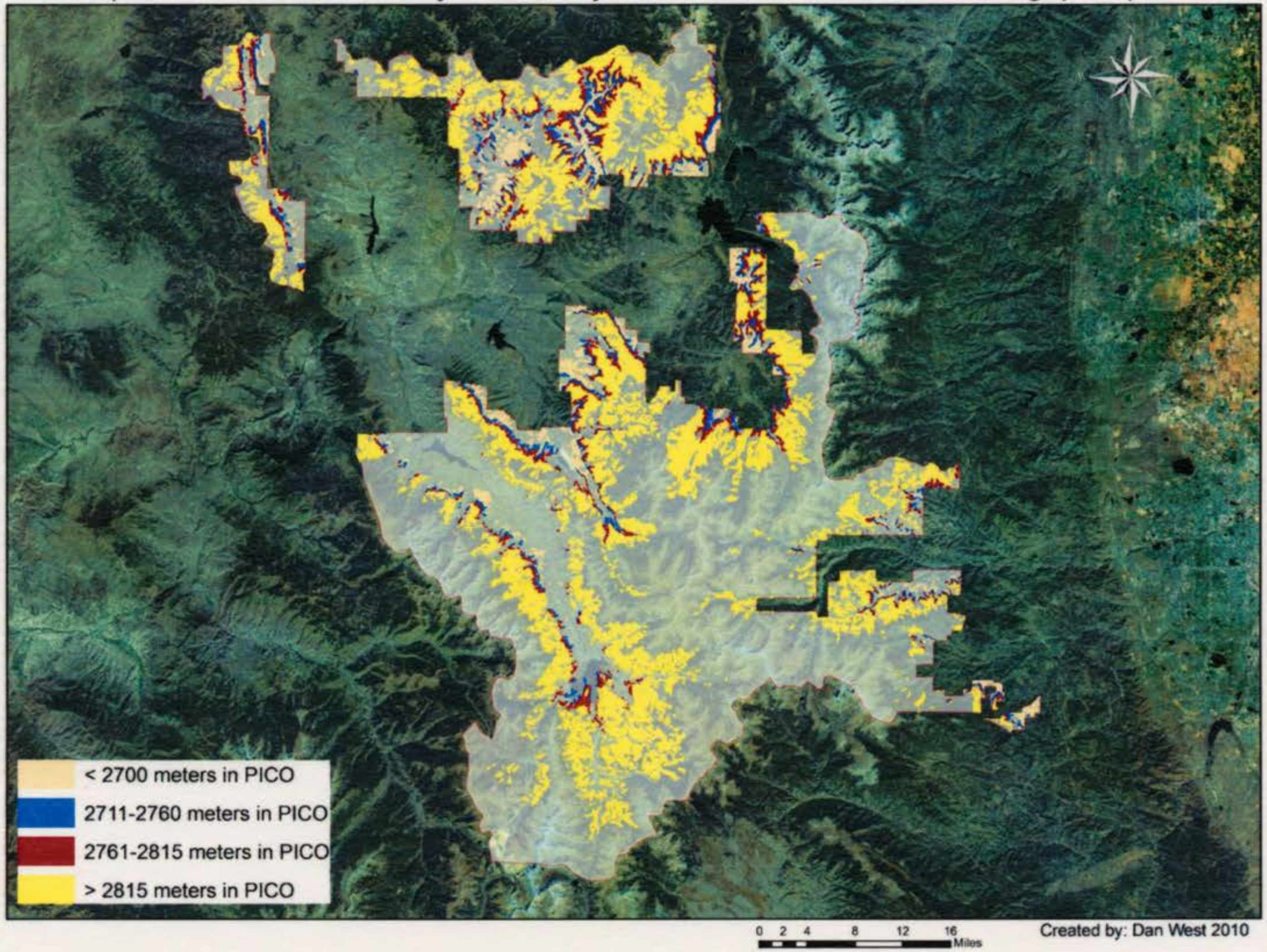


Figure 14. Arapaho National Forest, CO. joint probability surface of lightning-caused ignitions (1956-1979) occurring with mountain pine beetle-caused lodgepole pine mortality (1980-1987) in lodgepole pine dominated stands (species composition of lodgepole ≥ 50%).

Arapaho NF Joint Probability Surface by CDF Quartile in dominated lodgepole pine



Created by: Dan West 2010

Figure 15. White River National Forest, CO. joint probability surface of lightning-caused ignitions (1935-1979) occurring with mountain pine beetle-caused lodgepole pine mortality (1981-1987) in lodgepole pine dominated stands (species composition of lodgepole pine $\geq$ 50%).

White River NF Joint Probability Surface by CDF Quartile in dominated lodgepole pine

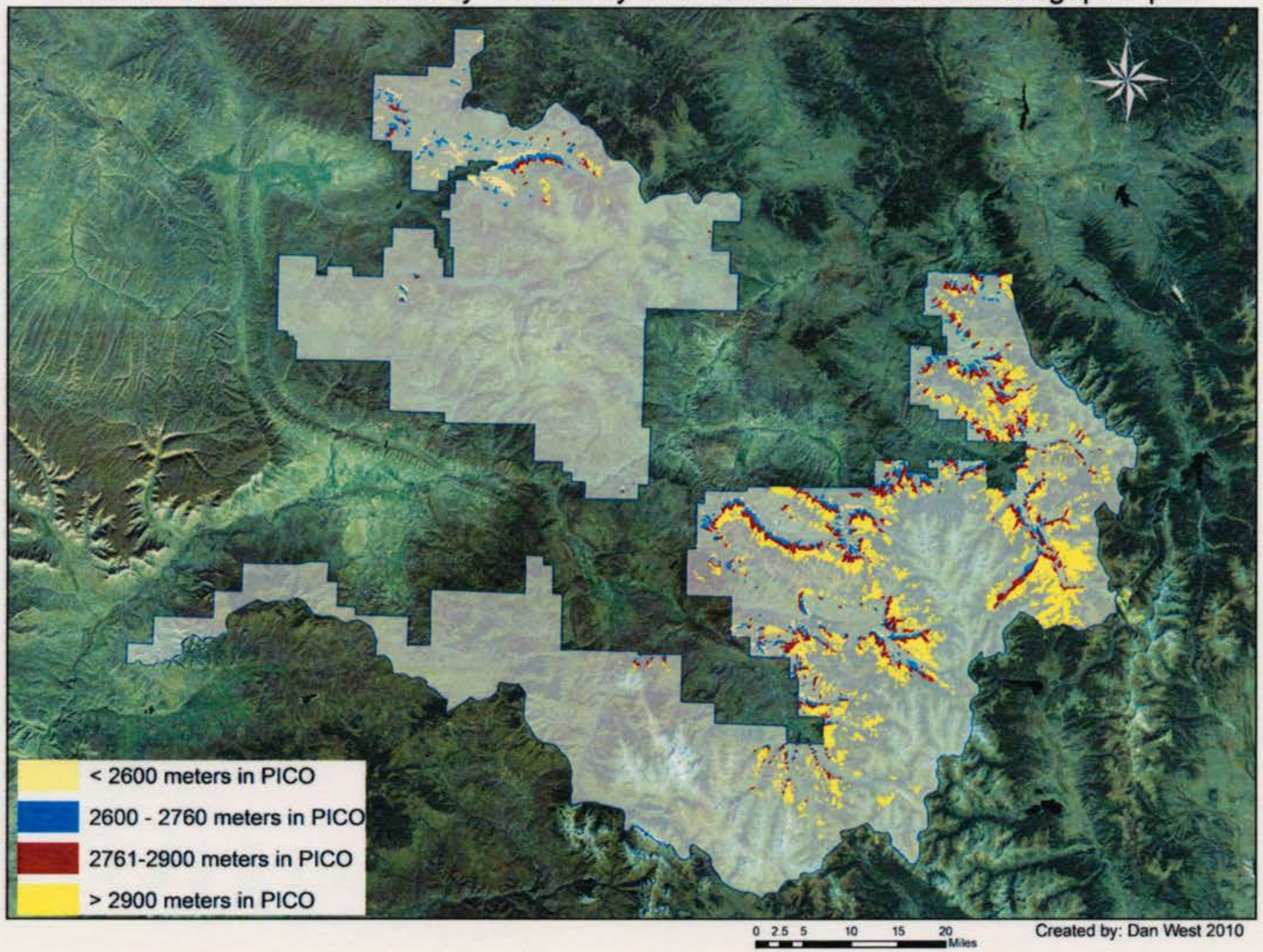


Figure 16. Arapaho National Forest, CO. directional cell chi square fire frequency in mountain pine beetle-caused lodgepole pine mortality (1980-2005) and annual maximum and minimum Palmer Modified Drought Index for Colorado Region 25.

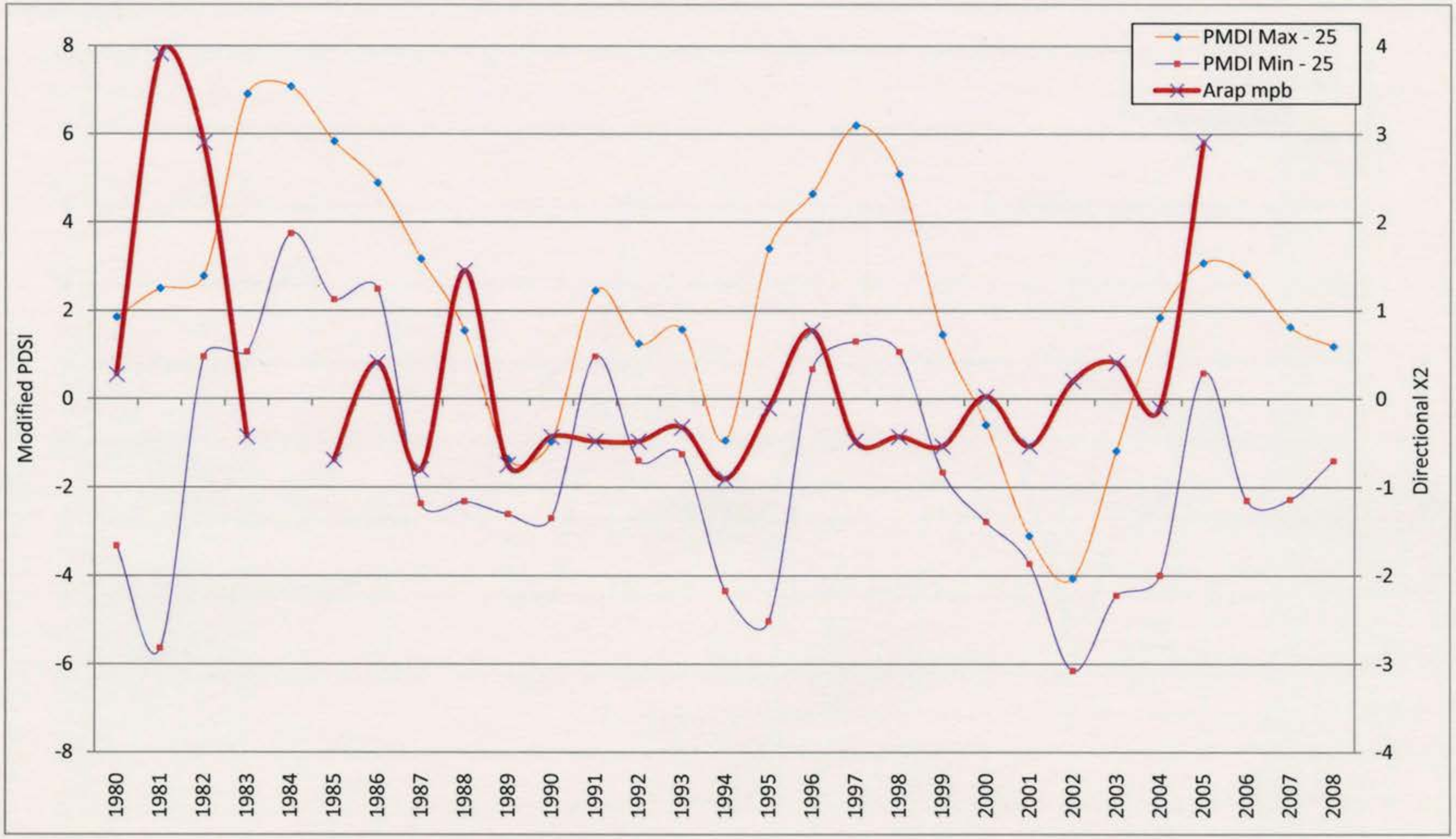


Figure 17. Arapaho National Forest, CO. directional cell chi square fire frequency in mountain pine beetle-caused lodgepole pine mortality (1980-2005) and annual maximum and minimum Palmer Modified Drought Index for Colorado Region 24 (1980-2008).

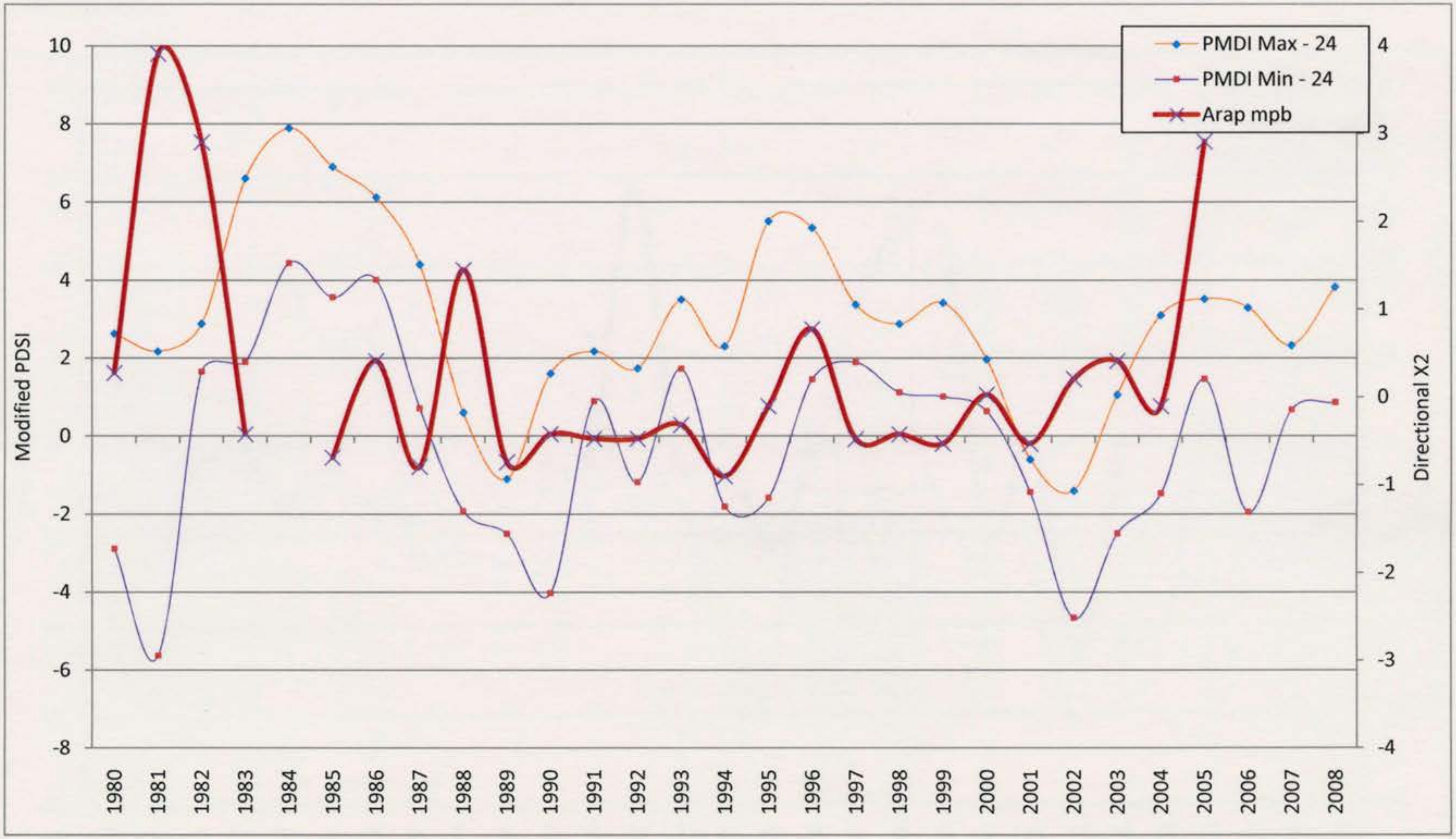


Figure 18. White River National Forest, CO. annual fire frequency directional cell chi square in mountain pine beetle-caused lodgepole pine mortality (1980-2003) and annual maximum and minimum Palmer Modified Drought Index for Colorado Region 25 (1980-2008).

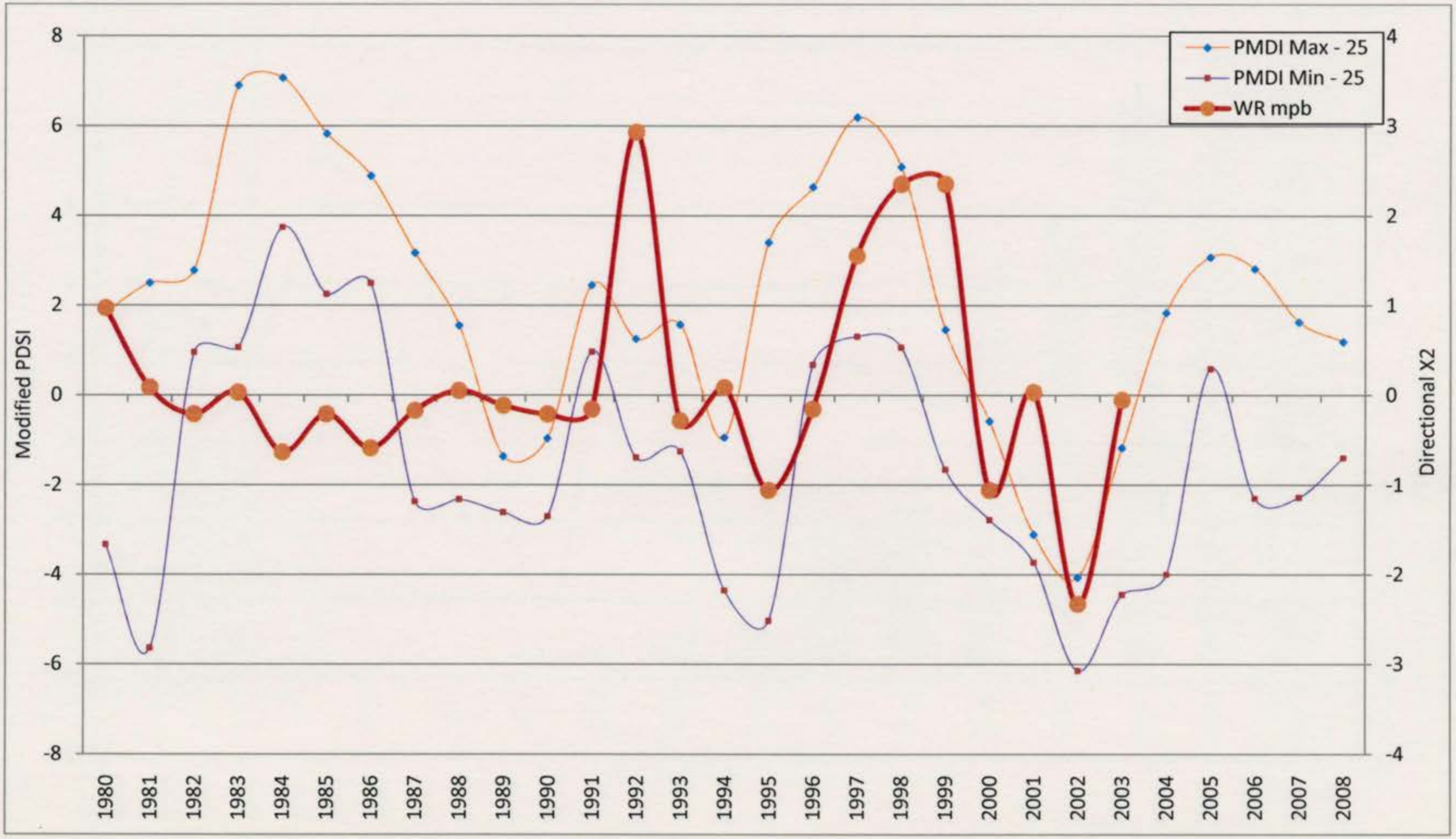


Figure 19. White River National Forest, CO. annual fire frequency directional cell chi square in mountain pine beetle-caused lodgepole pine mortality (1980-2003) and annual maximum and minimum Palmer Modified Drought Index for Colorado Region 24 (1980-2008).

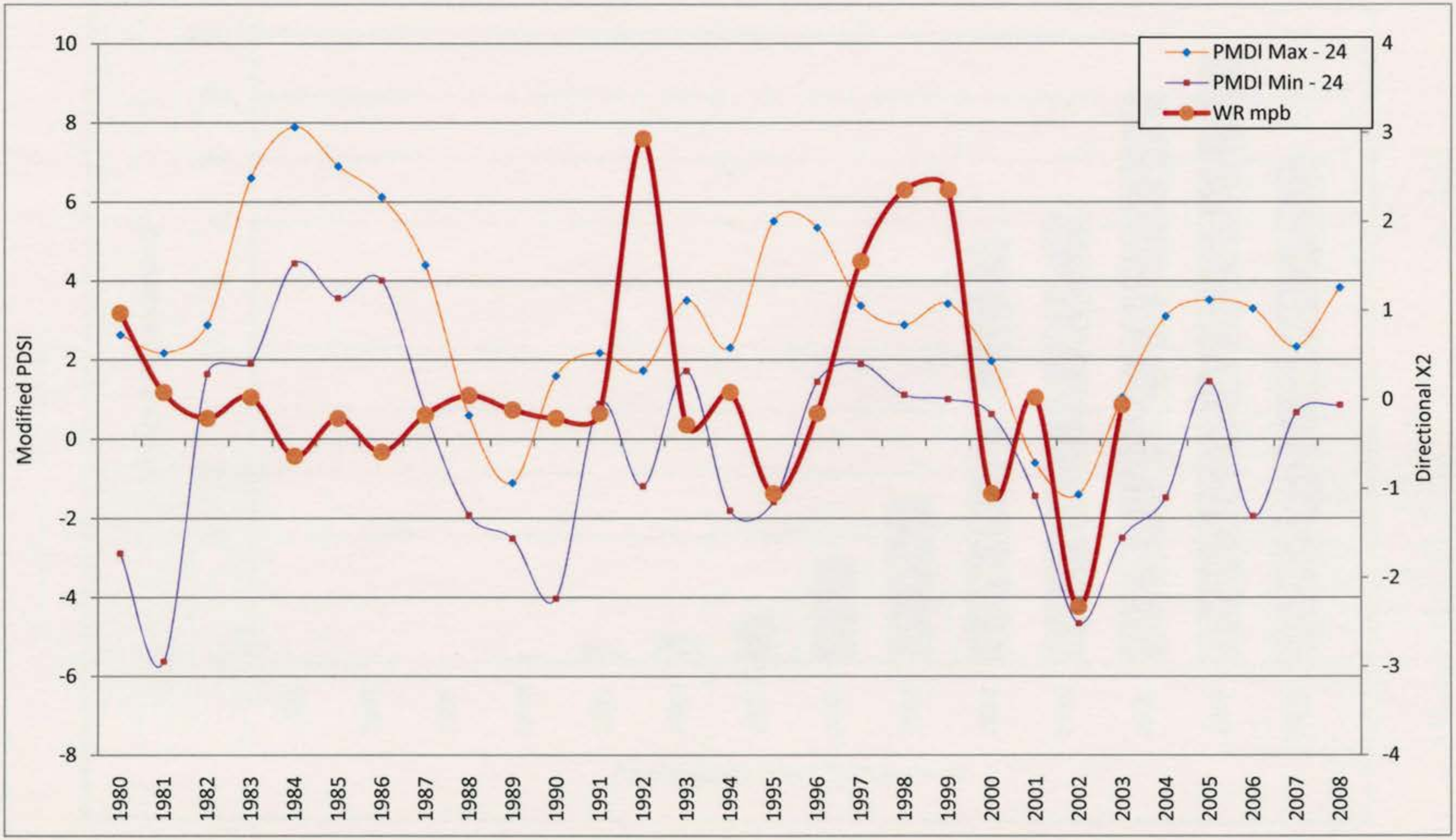
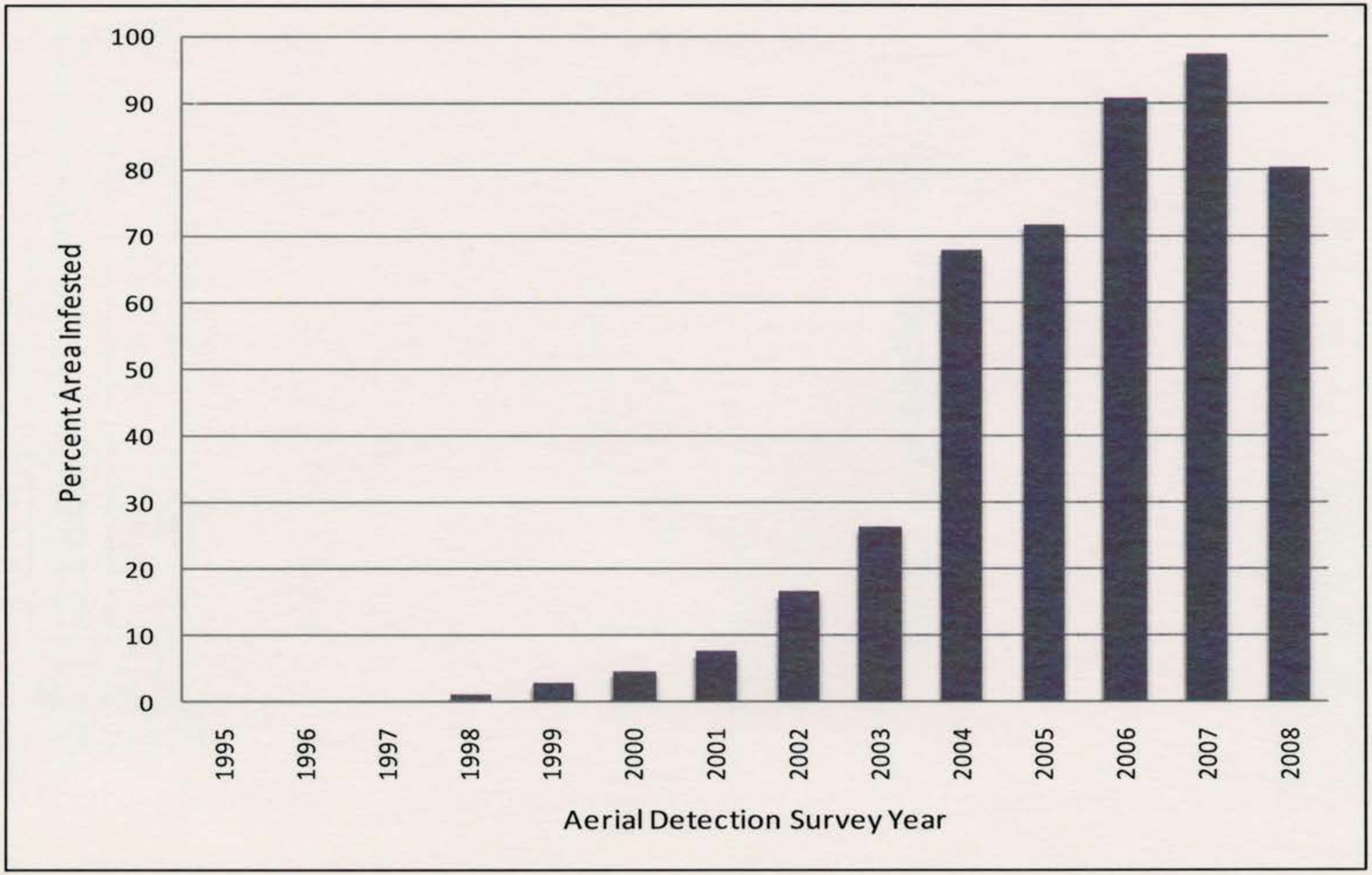


Figure 20. Annual percent lodgepole pine dominated stand area (lodgepole species composition ≥ 50%; 102,052 hectares; USDA Forest Service Region 2 R2Veg) affected by mountain pine beetle (USDA Forest Service Region 2 Aerieal Detection Survey): Arapaho NF (1995-2008)



APPENDICES

APPENDIX A: Supplementary Materials and Methods

USDA Forest Service Annual Reports

USDA Forest Service, Region 2, Forest Health Management Annual Reports (1975-2005) were used to identify where *D. ponderosae*-caused mortality was noted in lodgepole pine forests from 1980 through 1990. Widespread spatio-temporal mountain pine beetle-caused mortality was noted on the Arapaho National Forest (NF) from 1981-1986, on the Roosevelt NF from 1975-1982 and 1994-2000, on the White River NF in 1981-1987 and on the Uncompahgre NF from 1977 through 1991. Mountain pine beetle-caused mortality was also reported on the Routt, Medicine Bow, Pike - San Isabel, San Juan and Grand Mesa NFs but these events were reported over fewer years and were not included as part of this study (Table B1).

USDA Forest Service, Region 2, Annual Reports indicate the mountain pine beetle outbreak in Arapaho NF lodgepole pine forests occurred near Tabernash, Colorado beginning in 1981 and continued through 1987 (Table B1). From 1988 through 1991 a separate outbreak near Ute Pass was reported. The first report of what has now resulted in the current widespread mountain pine beetle epidemic began in 1992 near Lake Granby, Arapaho NF, CO.

Annual Reports indicate an increase in mountain pine beetle activity in 1980 on the White River NF near Minturn and Eagle, Colorado (Table B1). By 1987, the epidemic was reduced to a few locations north of Dillon Reservoir along the Blue River drainage and those infestations were reduced to endemic status by 1988.

Hardcopy USDA Forest Service Aerial Detection Survey

The USDA US Forest Service, Forest Health Management (FHM) Region 2 has conducted aerial surveys of forest overstory host species with various insect and disease damaging agents since 1956. Initially the aerial detection survey was conducted using hardcopy 1:250000 scale topographic maps and a system of colored symbols that represented various mortality agents and their observed estimated incidence. Aerial detection surveyors would allocate survey flight locations based on the general location of a known insect or disease activity previously identified by District foresters and support staff (Bailey, 2008). The information from the original flight map was subsequently transferred to US Forest Service, National Forest Recreation maps. The recreation maps contained a legend depicting the intensity of mortality by colored symbols (dots, circles, squares, triangles, etc.) representing damage agents.

Beginning in 1994, hardcopy hand drawn maps were replaced with a digital Aerial Detection Survey process. A modified version of the 1994 digital aerial detection recording, known as sketch mapping using laptop computers, is currently used by USDA Forest Service Region 2 aerial surveyors.

Hardcopy GIS georeferencing

Maps for five National Forests (Arapaho, Roosevelt, Routt, White River, Uncompahgre) were scanned at 300dpi in a Tagged Image File Format (TIFF) and further converted in Adobe Photoshop to a Joint Photographic Experts Group (JPEG) image to obtain monitor/computer screen pixel location values. Each pixel location associated with the corners of individual scanned maps was recorded for the purpose of creating a set of reference points. Each corner pixel referenced to a hand calculated decimal degree in WGS NAD 1927 from each USDA Forest Service Recreation Map was used to georeference and rectify each map in ESRI's ArcGIS geographical information system software. A dedicated tic file was generated to relate the corners of each map with their respective latitude and longitude and further rectified (Tables I.1, I.2). The rectification process creates a raster image with each pixel value correlated to a projected latitude and longitude.

Drought indices

The Colorado Climate Center has generated a Modified Palmer Drought Severity Index (PMDI) for the state of Colorado. The index is based on the Palmer Drought Severity Index (PDSI) which is derived from variables dictating moisture supply and demand. The modification calculates three indices based on the probability of a drought occurring under monthly observations (Heddinghause et al. 1991).

APPENDIX B: Supplementary Tables

Table B1. USDA Region 2, Forest Service Annual Report synopsis chronology of *Dendroctonus ponderosae* activity in ponderosa and lodgepole pine hosts in Colorado and southern Wyoming.

Outbreak Description	Host	Year(s) of MPB report
Front Range [6]	*Pinus ponderosa*	1975-1982, 1994-2000
Uncompahgre Plateau [8]	*Pinus ponderosa*	1976-1991, 1995-1996
Buena Vista [4]	*Pinus ponderosa*	1994-1996
Middle Park [3]	*Pinus contorta*	1975-1976
Rabbit Ears Mtn. [7]	*Pinus contorta*	1980-1981
Tabernash [1]	*Pinus contorta*	1981-1987
Minturn/Eagle [9]	*Pinus contorta*	1980-1987
Dillon Reservoir [9]	*Pinus contorta*	1983-1987
Taylor River [5]	*Pinus contorta*	1985
Ute Pass/ Pass Creek [1]	*Pinus contorta*	1989-1991
Granby Lake/Fraser Valley [1]	*Pinus contorta*	1992-Present
Vail Pass [9]	*Pinus contorta*	1996-2002

[1] Arapaho National Forest

[2] Grand Mesa National Forest

[3] Medicine Bow National Forest

[4] Pike San Isabel National Forest

[5] Rio Grande National Forest

[6] Roosevelt National Forest

[7] Routt National Forest

[8] San Juan - Uncompahgre NF

Table B2. Hardcopy USDA Forest Service Region 2, Aerial Detection Survey National Forest map scales and available years.

Map Scale 1:250,000		Map Scale USDA US Forest Service Recreation Map (variable)	
Forest	Years	Forest	Years
Arapaho NF	1956 – 1963, 1967-1970	Arapaho NF	1980 – 1987
Roosevelt NF	1956-1970	Roosevelt NF	1979-1986, 1989
Routt NF	1956-1970	Routt NF	1975, 1980-1990
Uncompahgre NF	1956-1970	Uncompahgre NF	1970-1971, 1973, 1980-1990
White River NF	1956-1970	White River NF	1981-1987

Table B3. Species covertypes (USDA Forest Service Region 2, R2Veg) selected with lodgepole pine (PICO;PICOL) composition of 50 percent or greater for the Arapaho and White River National Forests, CO.

Arapaho NF		
	Admin Forest	
	Arapaho	
		PICO, PICO:ABLA, PICO:ABLA:PIEN, PICO:ABLA:PIFL2, PICO:ABLA:PIPOS, PICO:ABLA:POTR5, PICO:ABLA:PSME, PICO:JUSC2, PICO:PIAR, PICO:PIAR:ABLA, PICO:PIAR:PIEN, PICO:PIAR:PIFL2, PICO:PIAR:POTR5, PICO:PIEN, PICO:PIEN:ABLA, PICO:PIEN:PIAR, PICO:PIEN:PIFL2, PICO:PIEN:PIPOS, PICO:PIEN:POTR5, PICO:PIEN:PSME, PICO:PIFL2, PICO:PIFL2:ABLA, PICO:PIFL2:PIAR, PICO:PIFL2:PIEN, PICO:PIFL2:PIPOS, PICO:PIFL2:POTR5, PICO:PIFL2:PSME, PICO:PIPO:POTR5, PICO:PIPOS, PICO:PIPOS:PIEN, PICO:PIPOS:PIFL2, PICO:PIPOS:POTR5, PICO:PIPOS:PSME, PICO:POTR5, PICO:POTR5:ABLA, PICO:POTR5:PIAR, PICO:POTR5:PIEN, PICO:POTR5:PIFL2, PICO:POTR5:PIPOS, PICO:POTR5:POAN3, PICO:POTR5:PSME, PICO:PSME, PICO:PSME:JUSC2, PICO:PSME:PIEN, PICO:PSME:PIFL2, PICO:PSME:PIPOS, PICO:PSME:POTR5
	Medicine Bow/Routt NF	
		PICO, PICO:ABLA, PICO:ABLA:PIEN, PICO:ABLA:POTR5, PICO:PIEN, PICO:PIEN:ABLA, PICO:PIEN:POTR5, PICO:POTR5, PICO:POTR5:ABLA, PICO:POTR5:PIEN
	White River NF	
		PICO, PICOL, PICOL:ABLA, PICOL:ABLA:PIEN, PICOL:ABLA:POTR5, PICOL:ABLA:PSME, PICOL:PIAR, PICOL:PIAR:POTR5,PICOL:PIEN, PICOL:PIEN:ABLA, PICOL:PIEN:PIFL2, PICOL:PIEN:POPUL, PICOL:PIEN:POTR5, PICOL:PIEN:PSME, PICOL:PIFL2, PICOL:PIFL2:PIEN, PICOL:PIPU, PICOL:PIPU:PIEN, PICOL:PIPU:POTR5, PICOL:POPUL, PICOL:POTR5, PICOL:POTR5:ABLA, PICOL:POTR5:PIEN, PICOL:POTR5:PSME, PICOL:PSME, PICOL:PSME:ABLA, PICOL:PSME:PIEN, PICOL:PSME:POTR5
White River NF		
	Admin Forest	
	White River NF	
		PICO, PICO:ABLA, PICO:ABLA:PIED, PICO:ABLA:PIEN, PICO:ABLA:POTR5, PICO:ABLA:PSME, PICO:PIEN, PICO:PIEN:ABLA, PICO:PIEN:POTR5, PICO:POTR5, PICO:POTR5:ABLA, PICO:POTR5:PIED, PICO:POTR5:PSME, PICO:PSME, PICO:PSME:ABLA, PICO:PSME:POTR5, PICOL, PICOL:ABLA, PICOL:ABLA:PIEN, PICOL:ABLA:POTR5, PICOL:ABLA:PSME, PICOL:PIEN, PICOL:PIEN:ABLA, PICOL:PIEN:ALINT, PICOL:PIEN:PIPU, PICOL:PIEN:POTR5, PICOL:PIEN:PSME, PICOL:PIPOS, PICOL:PIPU, PICOL:PIPU:ABLA, PICOL:PIPU:PIEN, PICOL:PIPU:POTR5, PICOL:POTR5, PICOL:POTR5:ABLA, PICOL:POTR5:PIEN, PICOL:POTR5:PIPU, PICOL:POTR5:PSME, PICOL:PSME, PICOL:PSME:ABLA, PICOL:PSME:PIEN, PICOL:PSME:PIPU, PICOL:PSME:POTR5

Table B4. Fire frequency on Colorado and southern Wyoming USDA Forest Service Region 2, National Forests (variable years).

National Forest	Fire Years	Frequency
Rio Grande	1960-1995	1,366
Routt	1970-2003	504
Med Bow	1970-2002	1,797
Pike-San Isabel	1970-2006	3,818
Grand Mesa-Uncompahgre-Gunnison	1970-2005	1,480
Arapaho	1958-2005	530
Roosevelt	1930-2005	2,820
White River	1933-2003	2,670

Table B5. Fire cause codes from USDA Forest Service, Region 2, fire point shapefile.

		Variables used in Lightning Analysis	
Fire Cause Code	Cause Description	Cause Code	Cause Description
1	Lightning	1	Lightning
2	Railroad	10	Fire cause codes 2 through 9
3	Equipment use		
4	Recreationist		
5	Smoking		
6	Debris Burning		
7	Arson		
8	Juveniles		
9	Miscellaneous		

Table B6. USDA Forest Service fire size (1980-2005) in hectares intersecting mountain pine beetle-caused mortality (1980-1987) areas.

	MPB[A]	Mean[B]	SD[C]	SE[D]	Median[E]	SE[F]	Max[G]	N[H]
Arapaho NF	no	1.68	17.4	1.13	0.04	1.10	196.3	249
	yes	0.41	1.1	4.78	0.04	0.29	4.0	14
White River NF	no	1.86	21.3	1.41	0.04	1.69	269.9	160
	yes	0.10	0.2	2.73	0.04	0.03	1.2	43

[A] Mountain pine beetle-caused mortality polygon presence (yes) or absence (no) intersection with fire occurrence

[B] Mean reported fire size in hectares

[C] Standard deviation of the mean fire size

[D] Standard error of the mean fire size

[E] Median reported fire size in hectares

[F] Standard error of the median fire size

[G] Maximum reported fire size in hectares

[H] Number of fire observations

Table B7. Reported size of fire occurrence on the Arapaho (1980-2005) and White River (1980-2003) NFs in the presence or absence of aerially detected mountain pine beetle-caused lodgepole pine mortality (1980-1987).

	Fire Cause[A]	MPB[B]	Mean[C]	SD[D]	SE[E]	Median[F]	SE[G]	Max[H]	N[I]
Arapaho NF	Lightning	no	0.134	0.33	2.17	0.04	0.04	2.0	68
		yes	0.785	1.50	6.78	0.04	0.57	4.0	7
	Human	no	2.258	20.40	1.33	0.04	1.52	196.3	181
		yes	0.040	0.00	6.78	0.04	0.00	0.0	7
White River NF	Lightning	no	0.193	0.62	2.51	0.04	0.09	3.6	51
		yes	0.094	0.09	7.32	0.08	0.04	0.2	6
	Human	no	2.639	25.86	1.72	0.04	2.48	269.9	109
		yes	0.101	0.24	2.95	0.04	0.04	1.2	37

[A] Cause of reported fires

[B] Mountain pine beetle-caused mortality polygon presence (yes) or absence (no) intersection with fire occurrence

[C] Mean reported fire size in hectares

[D] Standard deviation of the mean fire size

[E] Standard error of the mean fire size

[F] Median reported fire size in hectares

[G] Standard error of the median fire size

[H] Maximum reported fire size in hectares

[I] Number of fire observations

Table B8. Frequency of USDA Forest Service, Region 2, stand inventory plots with 20% or greater basal area in lodgepole pine measured between 1978 through 1993.

Arapaho NF	MPB[A]	Freq[B]	Percent[C]	Mean[D]	SD[E]	Range[F]
	No	11922	74.08	3.48	2.8	1 - 27
	Yes	4171	25.92	3.81	3.2	1 - 41
White River	No	10967	65.91	4.9	4.2	1 - 35
	Yes	5672	34.09	4.5	3.8	1 - 26

[A]GIS intersection of plots spatially occurring with aerially detected MPB-caused mortality ploygons

[B]Frequency of measured plots

[C]Percent of total plots

[D]Average per stand plot frequency

[E]Standard Deviation of plot frequency

[F]Range of plot frequency across all measured plots

Table B9. Annual cell chi square deviation from expected for the Arapaho and White River National Forests, CO. with maximum and minimum northern Rocky Mountain Region 24 and 25 Palmer Modified Drought Index values (Colorado Climate Center).

	Arapaho		White River		Region 25		Region 24	
	no mpb	mpb	no mpb	mpb	Max	Min	Max	Min
1980	-0.0154	0.2741	-0.2606	0.9696	1.85	-3.33	2.63	-2.89
1981	-0.2198	3.9099	-0.0222	0.0826	2.5	-5.64	2.17	-5.63
1982	-0.1631	2.9007	0.0569	-0.2118	2.78	0.95	2.88	1.65
1983	0.0239	-0.4259	-0.0074	0.0275	6.9	1.06	6.6	1.9
1984	*	*	0.1708	-0.6355	7.07	3.74	7.89	4.44
1985	0.0389	-0.692	0.0569	-0.2118	5.83	2.25	6.9	3.56
1986	-0.0231	0.4109	0.1586	-0.5903	4.89	2.49	6.12	4.01
1987	0.0449	-0.7985	0.0466	-0.1733	3.17	-2.37	4.4	0.71
1988	-0.0815	1.4503	-0.0125	0.0464	1.55	-2.32	0.6	-1.92
1989	0.0419	-0.7452	0.031	-0.1155	-1.36	-2.61	-1.11	-2.51
1990	0.0239	-0.4259	0.0569	-0.2118	-0.96	-2.7	1.6	-4.03
1991	0.0269	-0.4791	0.0422	-0.1572	2.45	0.96	2.17	0.89
1992	0.0269	-0.4791	-0.7874	2.93	1.25	-1.39	1.73	-1.19
1993	0.018	-0.3194	0.0765	-0.2847	1.57	-1.25	3.5	1.72
1994	0.0509	-0.9049	-0.0222	0.0826	-0.94	-4.35	2.3	-1.81
1995	0.006	-0.1065	0.2846	-1.0591	3.4	-5.03	5.51	-1.59
1996	-0.0435	0.7741	0.0422	-0.1572	4.64	0.67	5.34	1.45
1997	0.0269	-0.4791	-0.4172	1.5525	6.19	1.3	3.37	1.89
1998	0.0239	-0.4259	-0.6322	2.3523	5.09	1.06	2.88	1.12
1999	0.0299	-0.5323	-0.6322	2.3523	1.46	-1.66	3.42	1.01
2000	-0.0015	0.0258	0.2846	-1.0591	-0.58	-2.78	1.97	0.63
2001	0.0299	-0.5323	-0.0074	0.0275	-3.1	-3.73	-0.6	-1.44
2002	-0.0115	0.2043	0.6262	-2.33	-4.06	-6.15	-1.4	-4.66
2003	-0.0231	0.4109	0.0155	-0.0578	-1.17	-4.45	1.06	-2.5
2004	0.006	-0.1065	N/A	N/A	1.84	-4	3.1	-1.48
2005	-0.1636	2.9094	N/A	N/A	3.08	0.58	3.52	1.46

* No fire frequency in 1984

Table B10. Human and lightning-caused fire ignitions per decade per 100,000 ac on the Arapaho (1980-2005) and White River (1980-2003) NFs occurring with/without aerially detected mountain pine beetle-caused mortality.

White River National Forest		Arapaho National Forest	
Fire Years post-MPB initiation (1980-2003)		Fire Years post-MPB initiation (1980-2005)	
Ignitions per decade/100,000 ac		Ignitions per decade/100,000 ac	
MPB	9.1	MPB	9.6
NF w/o MPB	3.6	NF w/o MPB	9.1

Table B11. White River NF referenced tic coordinates from USDA Forest Service Recreation Maps containing Aerial Detection Survey mountain pine beetle-caused mortality (1981-1987).

White River National Forest		Pixel X	Pixel Y	Longitude	Latitude
1981	North	542.497	-422.500	-108.00000	39.58624
		5641.500	-479.500	-107.99875	40.08333
		7448.500	-1791.502	-107.83313	40.25820
		7442.486	-10363.498	-106.75000	40.25913
		4354.522	-16325.500	-106.00000	39.95222
		540.500	-16381.501	-106.00000	39.58133
	South	2836.504	-407.481	-108.16792	39.19271
		6010.501	-447.512	-108.16717	39.50000
		7249.498	-1786.508	-108.00000	39.62153
		7122.501	-16398.493	-106.16557	39.61337
		2747.506	-16440.494	-106.16566	39.18372
		249.51	-14674.498	-106.39211	38.94477
		237.498	-6244.499	-107.44048	38.94535
		2182.503	-4132.502	-107.70313	39.13314
1982	North	480.496	-511.519	-108.00000	39.58624
		5607.498	-581.496	-107.99875	40.08333
		7405.491	-1910.499	-107.83313	40.25820
		7346.500	-10504.499	-106.75000	40.25913
		4205.500	-16457.504	-106.00000	39.95222
		386.514	-16487.502	-106.00000	39.58133
	South	2800.500	-399.493	-108.16792	39.19271
		5980.503	-420.507	-108.16717	39.50000
		7227.509	-1752.495	-108.00000	39.62153
		7184.481	-16397.474	-106.16557	39.61337
		2772.488	-16460.497	-106.16566	39.18372
		276.513	-14682.490	-106.39211	38.94477
		235.497	-6253.519	-107.44048	38.94535
		2168.502	-4126.507	-107.70313	39.13314
1983	North	551.501	-425.498	-108.00000	39.58624
		5647.486	-495.497	-107.99875	40.08333
		7444.493	-1816.503	-107.83313	40.25820
		7415.501	-10382.501	-106.75000	40.25913
		4319.503	-16329.509	-106.00000	39.95222
		507.508	-16380.495	-106.00000	39.58133
	South	3037.519	-399.515	-108.16792	39.19271
		6214.499	-419.501	-108.16717	39.50000
		7459.480	-1747.496	-108.00000	39.62153
		7421.500	-16357.499	-106.16557	39.61337
		3055.501	-16430.495	-106.16566	39.18372
		546.503	-14675.501	-106.39211	38.94477
		477.503	-6248.497	-107.44048	38.94535
		2408.514	-4123.505	-107.70313	39.13314

White River National Forest				
	Pixel X	Pixel Y	Longitude	Latitude
1984 North	573.527	-460.520	-108.00000	39.58624
	5673.488	-488.523	-107.99875	40.08333
	7486.501	-1790.503	-107.83313	40.25820
	7519.498	-10374.500	-106.75000	40.25913
	4451.507	-16351.508	-106.00000	39.95222
	640.504	-16421.499	-106.00000	39.58133
South	3047.503	-394.501	-108.16792	39.19271
	6225.503	-409.502	-108.16717	39.50000
	7474.495	-1737.499	-108.00000	39.62153
	7442.499	-16373.495	-106.16557	39.61337
	3054.499	-16438.504	-106.16566	39.18372
	550.499	-14673.498	-106.39211	38.94477
	494.490	-6248.490	-107.44048	38.94535
	2423.503	-4119.500	-107.70313	39.13314
1985 North	572.495	-507.510	-108.00000	39.58624
	5690.475	-548.519	-107.99875	40.08333
	7497.488	-1861.479	-107.83313	40.25820
	7500.498	-10447.513	-106.75000	40.25913
	4407.506	-16418.480	-106.00000	39.95222
	591.498	-16469.534	-106.00000	39.58133
South	2804.497	-368.496	-108.16792	39.19271
	5984.500	-403.504	-108.16717	39.50000
	7225.492	-1744.501	-108.00000	39.62153
	7111.502	-16373.499	-106.16557	39.61337
	2700.500	-16417.505	-106.16566	39.18372
	213.501	-14632.506	-106.39211	38.94477
	211.506	-6208.509	-107.44048	38.94535
	2155.507	-4092.499	-107.70313	39.13314
1986 North	571.675	-517.963	-108.00000	39.58624
	5696.477	-573.498	-107.99875	40.08333
	7498.499	-1895.532	-107.83313	40.25820
	7462.476	-10490.472	-106.75000	40.25913
	4338.472	-16451.559	-106.00000	39.95222
	517.504	-16486.493	-106.00000	39.58133
South	2799.502	-369.501	-108.16792	39.19271
	5981.492	-390.512	-108.16717	39.50000
	7230.488	-1725.501	-108.00000	39.62153
	7194.486	-16369.486	-106.16557	39.61337
	2780.516	-16431.502	-106.16566	39.18372
	282.506	-14660.487	-106.39211	38.94477
	236.504	-6228.509	-107.44048	38.94535
	2170.503	-4104.493	-107.70313	39.13314

White River National Forest					
		Pixel X	Pixel Y	Longitude	Latitude
1987	North	563.832	-521.067	-108.00000	39.58624
		5682.958	-549.927	-107.99875	40.08333
		7491.527	-1859.534	-107.83313	40.25820
		7498.492	-10452.492	-106.75000	40.25913
		4406.500	-16429.498	-106.00000	39.95222
	South	588.507	-16489.500	-106.00000	39.58133
		3020.496	-374.500	-108.16792	39.19271
		6200.491	-403.509	-108.16717	39.50000
		7446.508	-1742.492	-108.00000	39.62153
		7376.501	-16386.493	-106.16566	39.61337
		2966.506	-16437.502	-106.16566	39.18372
		474.504	-14664.494	-106.39211	38.94477
		447.518	-6230.519	-107.44048	38.94535
		2384.498	-4111.503	-107.70313	39.13314

Table B12. Arapaho NF referenced tic coordinates from USDA Forest Service Recreation Maps containing Aerial Detection Survey MPB-caused mortality (1981-1987).

Arapaho National Forest				
	Pixel X	Pixel Y	Longitude	Latitude
1980 North	465.078	-458.071	-106.70600	39.77960
	7386.866	-584.695	-106.70600	40.44720
	7236.014	-12098.044	-105.25000	40.44720
	345.063	-12087.153	-105.25000	39.77960
South	3063.498	-1936.504	-105.16136	39.78500
	7419.498	-1947.496	-105.16364	39.34880
	7337.487	-10909.496	-106.28409	39.34942
	4804.501	-12230.501	-106.45227	39.59360
	447.496	-12209.491	-106.45455	40.01802
	507.500	-4368.493	-105.46611	40.01852
1981 North	465.078	-458.071	-106.70600	39.77960
	7386.866	-584.695	-106.70600	40.44720
	7236.014	-12098.044	-105.25000	40.44720
	345.063	-12087.153	-105.25000	39.77960
South	3022.503	-1934.504	-105.16136	39.78500
	7377.497	-1904.501	-105.16364	39.34880
	7371.498	-10878.505	-106.28409	39.34942
	4857.506	-12218.493	-106.45227	39.59360
	496.505	-12232.506	-106.45455	40.01802
	489.504	-4390.500	-105.46611	40.01852
1982 North	465.078	-458.071	-106.70600	39.77960
	7386.866	-584.695	-106.70600	40.44720
	7236.014	-12098.044	-105.25000	40.44720
	345.063	-12087.153	-105.25000	39.77960
South	3066.504	-1936.503	-105.16136	39.78500
	7422.508	-1959.505	-105.16364	39.34880
	7313.506	-10925.518	-106.28409	39.34942
	4775.490	-12237.504	-106.45227	39.59360
	415.506	-12201.495	-106.45455	40.01802
	503.502	-4362.493	-105.46611	40.01852
1983 North	465.078	-458.071	-106.70600	39.77960
	7386.866	-584.695	-106.70600	40.44720
	7236.014	-12098.044	-105.25000	40.44720
	345.063	-12087.153	-105.25000	39.77960
South	3056.499	-1947.502	-105.16136	39.78500
	7412.499	-1933.506	-105.16364	39.34880
	7381.498	-10911.500	-106.28409	39.34942
	4859.493	-12246.490	-106.45227	39.59360
	496.507	-12252.506	-106.45455	40.01802
	513.505	-4394.504	-105.46611	40.01852

Arapaho National Forest				
	Pixel X	Pixel Y	Longitude	Latitude
1984 North	465.078	-458.071	-106.70600	39.77960
	7386.866	-584.695	-106.70600	40.44720
	7236.014	-12098.044	-105.25000	40.44720
	345.063	-12087.153	-105.25000	39.77960
South	3044.499	-1924.498	-105.16136	39.78500
	7399.509	-1916.502	-105.16364	39.34880
	7360.503	-10884.497	-106.28409	39.34942
	4829.503	-12215.502	-106.45227	39.59360
	471.504	-12210.502	-106.45455	40.01802
	500.507	-4369.512	-105.46611	40.01852
1985 North	465.078	-458.071	-105.25000	40.44720
	7386.866	-584.695	-105.25000	39.77960
	7236.014	-12098.044	-106.70600	39.77960
	345.063	-12087.153	-106.70600	40.44472
South	3006.511	-1970.502	-105.16136	39.78500
	7359.502	-1938.506	-105.16364	39.34880
	7369.502	-10899.502	-106.28409	39.34942
	4851.494	-12249.509	-106.45227	39.59360
	486.505	-12269.499	-106.45455	40.01802
	473.499	-4424.500	-105.46611	40.01852
1986 North	465.078	-458.071	-106.70600	39.77960
	7386.866	-584.695	-106.70600	40.44720
	7236.014	-12098.044	-105.25000	40.44720
	345.063	-12087.153	-105.25000	39.77960
South	3056.507	-1902.493	-105.16136	39.78500
	7412.496	-1884.499	-105.16364	39.34880
	7389.499	-10857.481	-106.28409	39.34942
	4866.491	-12189.498	-106.45227	39.59360
	504.518	-12196.500	-106.45455	40.01802
	518.488	-4353.497	-105.46611	40.01852
1987 North	504.373	-480.120	-106.70600	40.44720
	12018.457	-523.219	-105.25000	40.44720
	12064.049	-7427.444	-105.25000	39.77960
	437.837	-7397.342	-106.70600	39.77960
South	3253.522	-2060.496	-105.16136	39.78500
	7612.506	-2060.499	-105.16364	39.34880
	7557.497	-10989.484	-106.28409	39.34942
	5026.497	-12311.496	-106.45227	39.59360
	656.504	-12298.491	-106.45455	40.01802
	701.511	-4496.477	-105.46611	40.01852

Table B13. Fire occurrence on the White River National Forest (1980-2003) in the presence or absence of previous USDA Forest Service, Region 2 Aerial Detection Survey mountain pine beetle-caused lodgepole pine mortality (1981-1987).

	Year	Frequency	Percent	Cumulative Frequency	Cumulative Percent
White River without MPB intersection	1980	13	8.13	13	8.13
	1981	9	5.63	22	13.75
	1982	1	0.63	23	14.38
	1983	3	1.88	26	16.25
	1984	3	1.88	29	18.13
	1985	1	0.63	30	18.75
	1986	9	5.63	39	24.38
	1987	15	9.38	54	33.75
	1988	27	16.88	81	50.63
	1989	10	6.25	91	56.88
	1990	1	0.63	92	57.5
	1991	6	3.75	98	61.25
	1992	1	0.63	99	61.88
	1993	7	4.38	106	66.25
	1994	9	5.63	115	71.88
	1995	5	3.13	120	75
	1996	6	3.75	126	78.75
	1997	4	2.5	130	81.25
	1998	3	1.88	133	83.13
	1999	3	1.88	136	85
	2000	5	3.13	141	88.13
	2001	3	1.88	144	90
	2002	11	6.88	155	96.88
	2003	5	3.13	160	100
White River with MPB intersection	1980	6	13.95	6	13.95
	1981	3	6.98	9	20.93
	1983	1	2.33	10	23.26
	1986	1	2.33	11	25.58
	1987	3	6.98	14	32.56
	1988	8	18.6	22	51.16
	1989	2	4.65	24	55.81
	1991	1	2.33	25	58.14
	1992	2	4.65	27	62.79
	1993	1	2.33	28	65.12
	1994	3	6.98	31	72.09
	1996	1	2.33	32	74.42
	1997	3	6.98	35	81.4
	1998	3	6.98	38	88.37
	1999	3	6.98	41	95.35
	2001	1	2.33	42	97.67
	2003	1	2.33	43	100

Table B14. Annual fire occurrence (Arapaho NF 1980-2005) in the presence or absence of previous USDA Forest Service, Region 2 Aerial Detection Survey mountain pine beetle-caused lodgepole pine mortality (1980-1987).

	Year	Freq	Percent	Cumulative Frequency	Cumulative Percent
Arapaho NF without MPB intersection	1980	24	9.64	24	9.64
	1981	16	6.43	40	16.06
	1982	10	4.02	50	20.08
	1983	8	3.21	58	23.29
	1985	13	5.22	71	28.51
	1986	9	3.61	80	32.13
	1987	15	6.02	95	38.15
	1988	5	2.01	100	40.16
	1989	14	5.62	114	45.78
	1990	8	3.21	122	49
	1991	9	3.61	131	52.61
	1992	9	3.61	140	56.22
	1993	6	2.41	146	58.63
	1994	17	6.83	163	65.46
	1995	2	0.8	165	66.27
	1996	7	2.81	172	69.08
	1997	9	3.61	181	72.69
	1998	8	3.21	189	75.9
	1999	10	4.02	199	79.92
	2000	15	6.02	214	85.94
	2001	10	4.02	224	89.96
	2002	11	4.42	235	94.38
	2003	9	3.61	244	97.99
	2004	2	0.8	246	98.8
	2005	3	1.2	249	100
Arapaho NF with MPB intersection	1980	2	14.29	2	14.29
	1981	3	21.43	5	35.71
	1982	2	14.29	7	50
	1986	1	7.14	8	57.14
	1988	1	7.14	9	64.29
	1996	1	7.14	10	71.43
	2000	1	7.14	11	78.57
	2002	1	7.14	12	85.71
	2003	1	7.14	13	92.86
	2005	1	7.14	14	100

APPENDIX C: Supplementary Figures

Figure C1. *Pinus contorta* species range in North America (Little 1971).

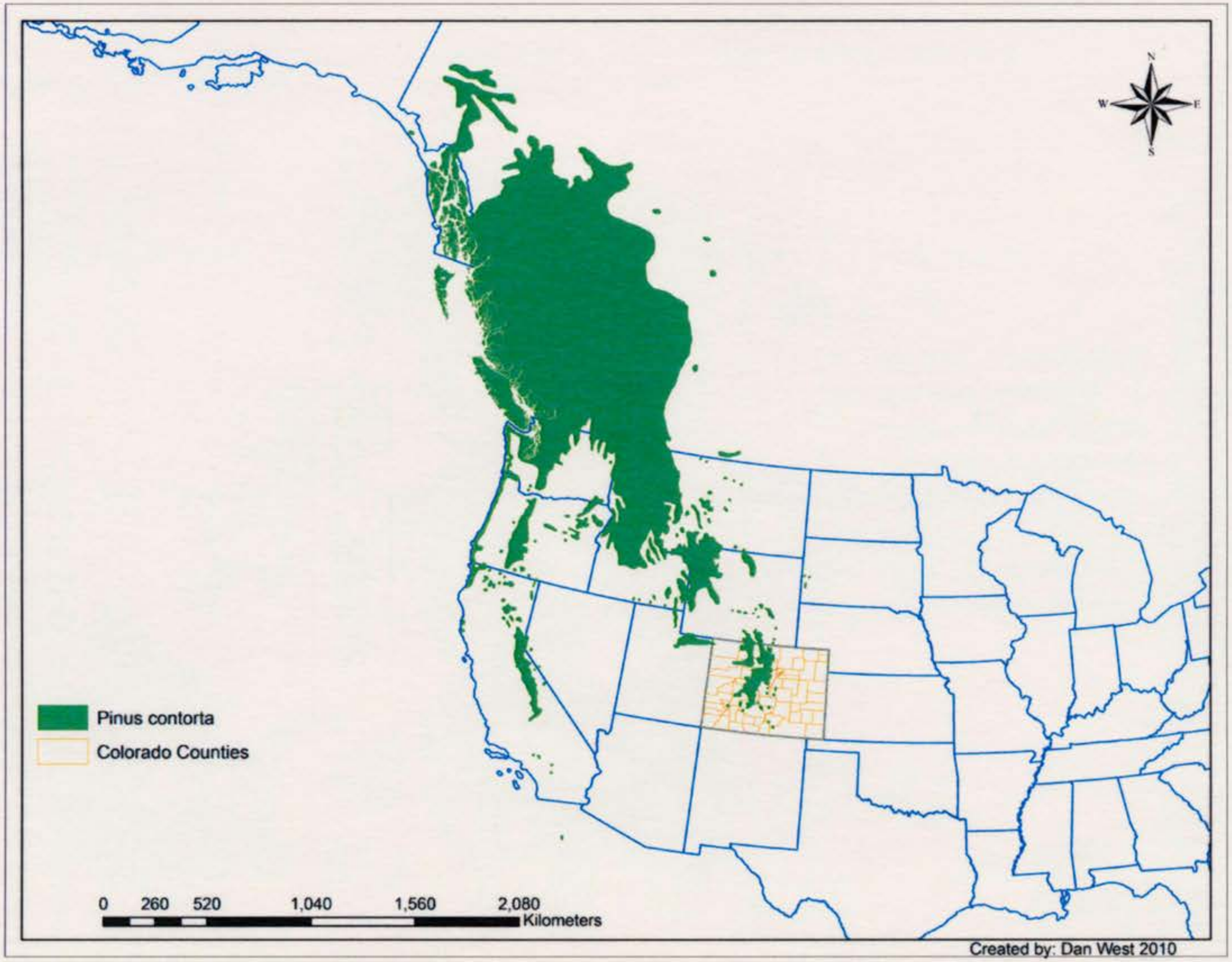
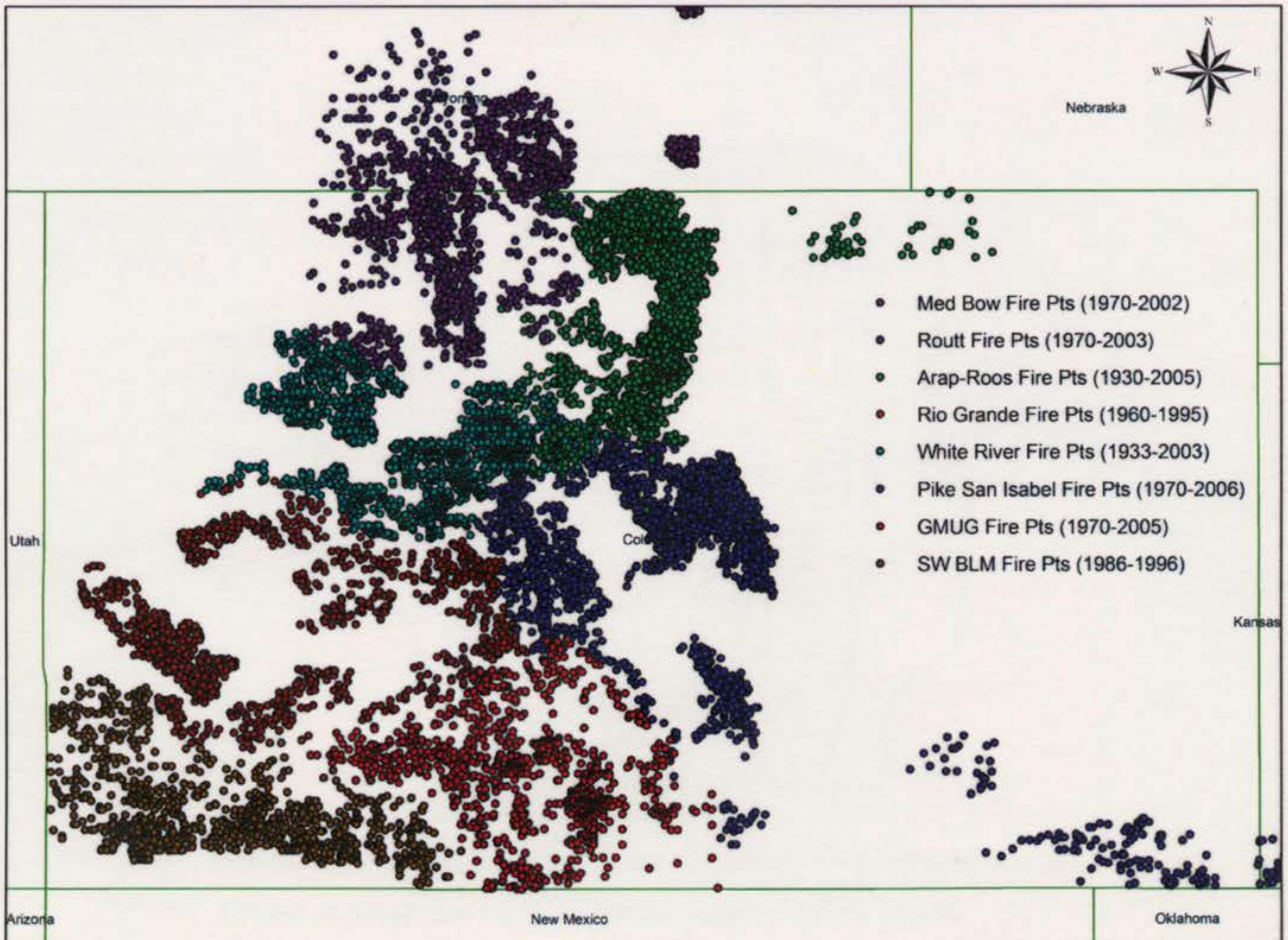

N
W
E
S
Pinus contorta
Colorado Counties
0 260 520 1,040 1,560 2,080
Kilometers
Created by: Dan West 2010

Figure C2. USDA Forest Service Region 2 fire point histories by National Forest (variable years) in Colorado and southern Wyoming.

USDA Forest Service Region 2 Fire Points by National Forest



Created by: Dan West 2008

Figure C3. Visual depiction of fire point field assessment methods. Cardinal direction surveys were conducted and cruised for remnant Course Woody Debris with evidence of mountain pine beetle.

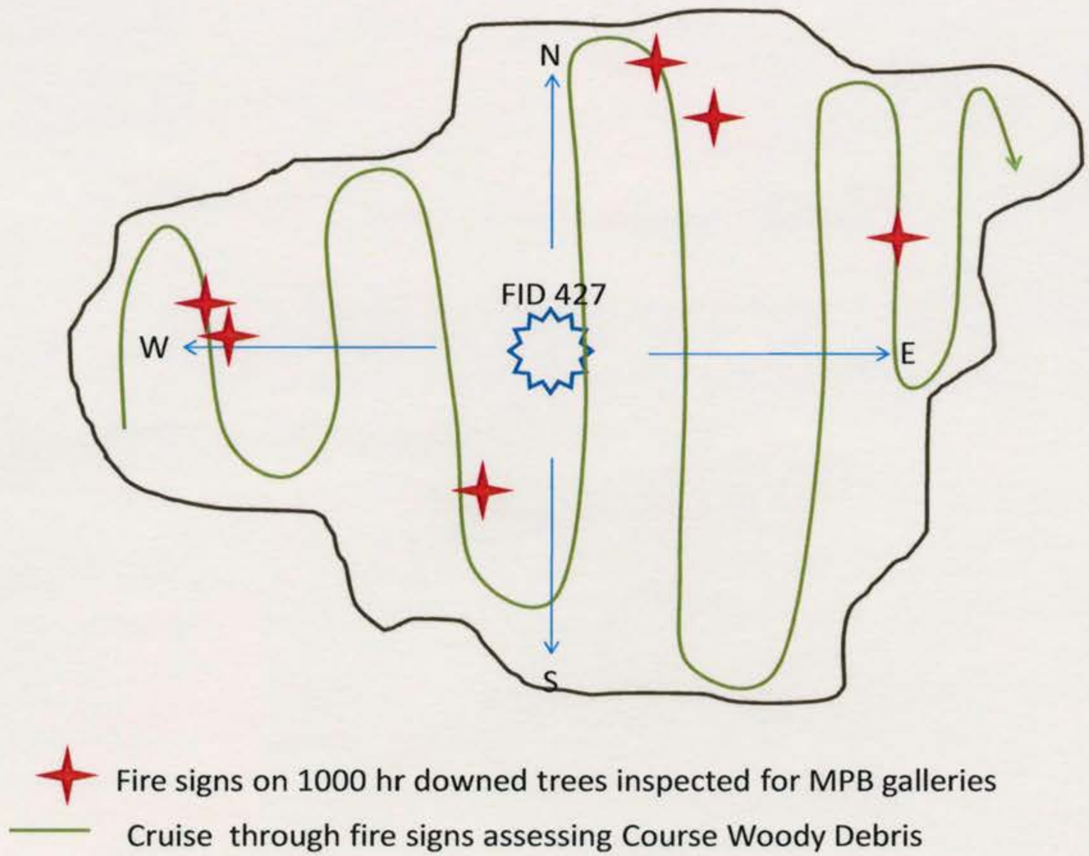


Figure C4. Arapaho National Forest, CO. USDA Forest Service Region 2 Aerial Detection Survey mountain pine beetle-caused lodgepole pine mortality with 50 meter and 500 meter buffers.

Arapaho NF Buffered ADS (1980-1987)

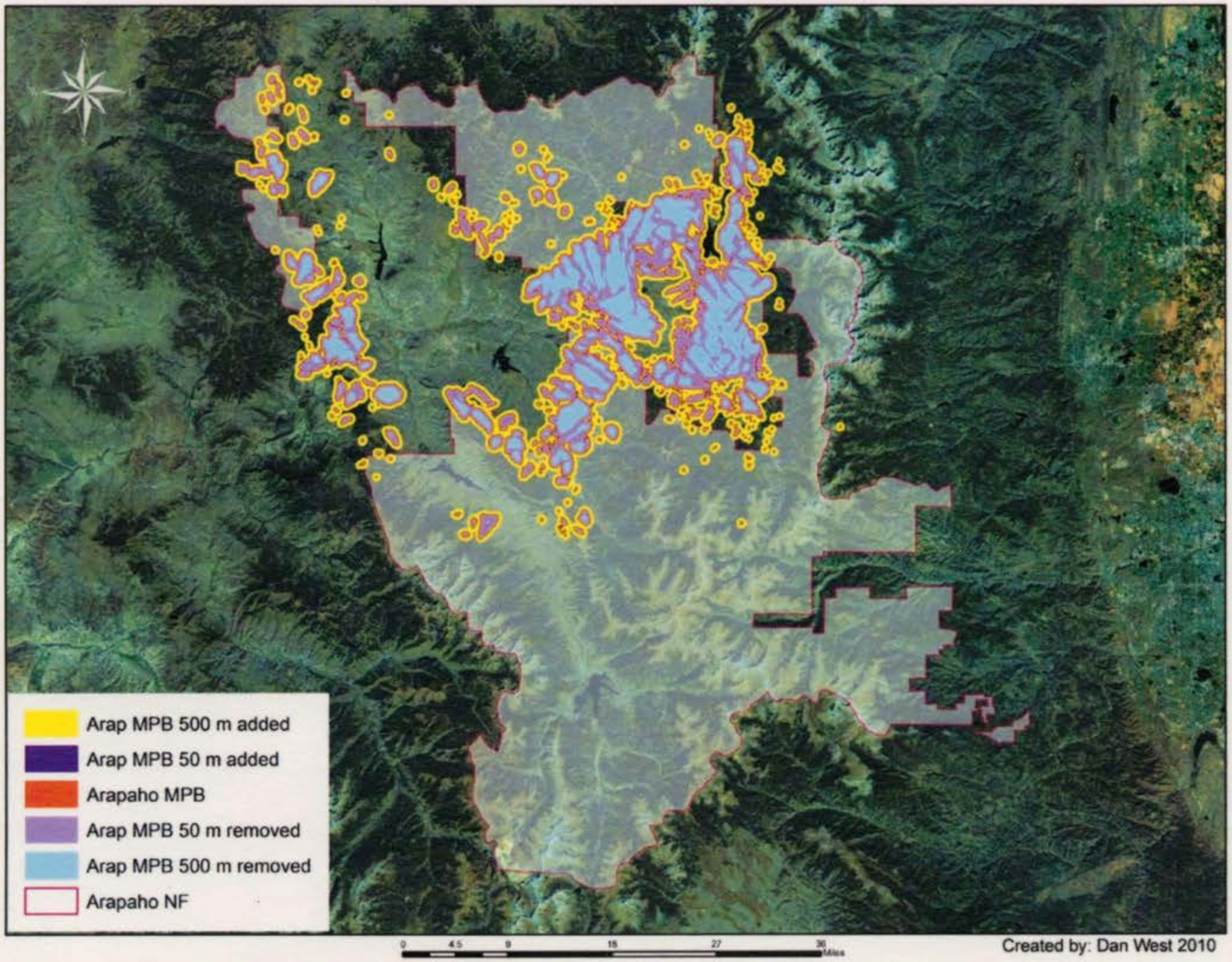


Figure C5. White River National Forest, CO. USDA Forest Service Region 2 Aerial Detection Survey mountain pine beetle-caused lodgepole pine mortality with 50 meter and 500 meter buffers.

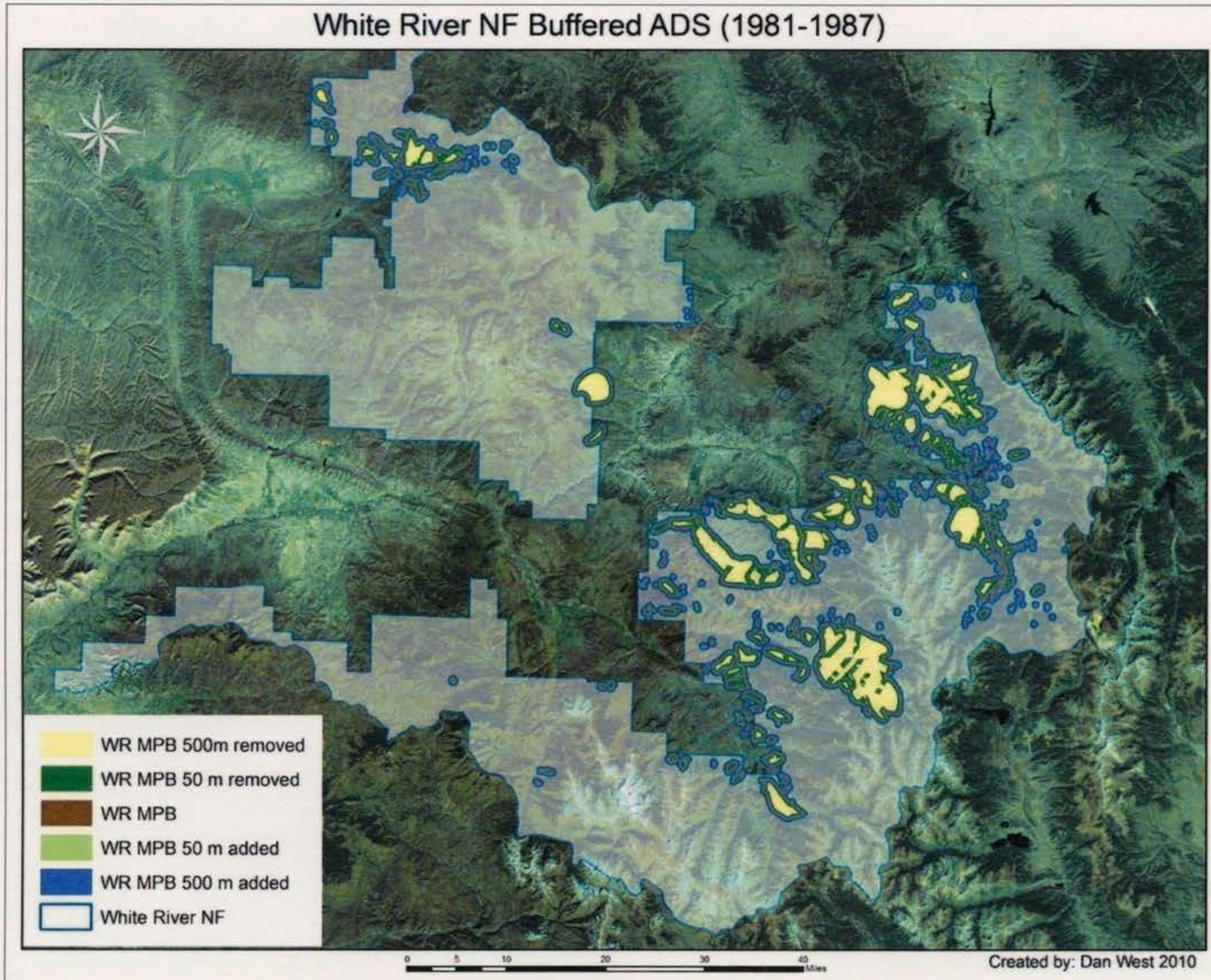

White River NF Buffered ADS (1981-1987)
WR MPB 500m removed
WR MPB 50 m removed
WR MPB
WR MPB 50 m added
WR MPB 500 m added
White River NF
0
5
10
20
30
40
Miles
Created by: Dan West 2010

Figure C6. Palmer Drought Severity Index Regions (Colorado Climate Center) for the USDA Forest Service Arapaho National Forest, CO.

Arapaho NF PDSI Regions

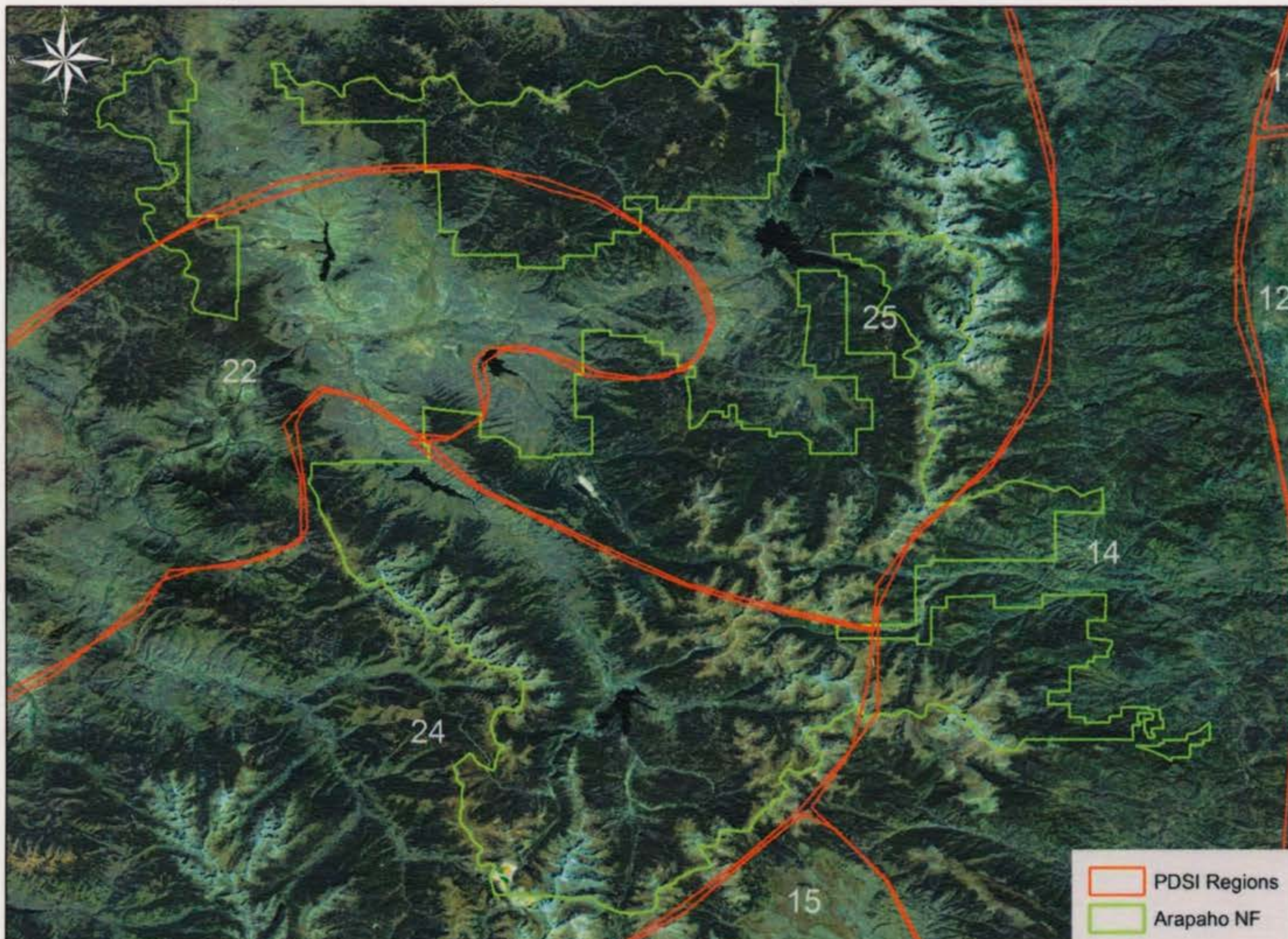


Figure C7. Palmer Drought Severity Index Regions (Colorado Climate Center) for the USDA Forest Service White River National Forest, CO.

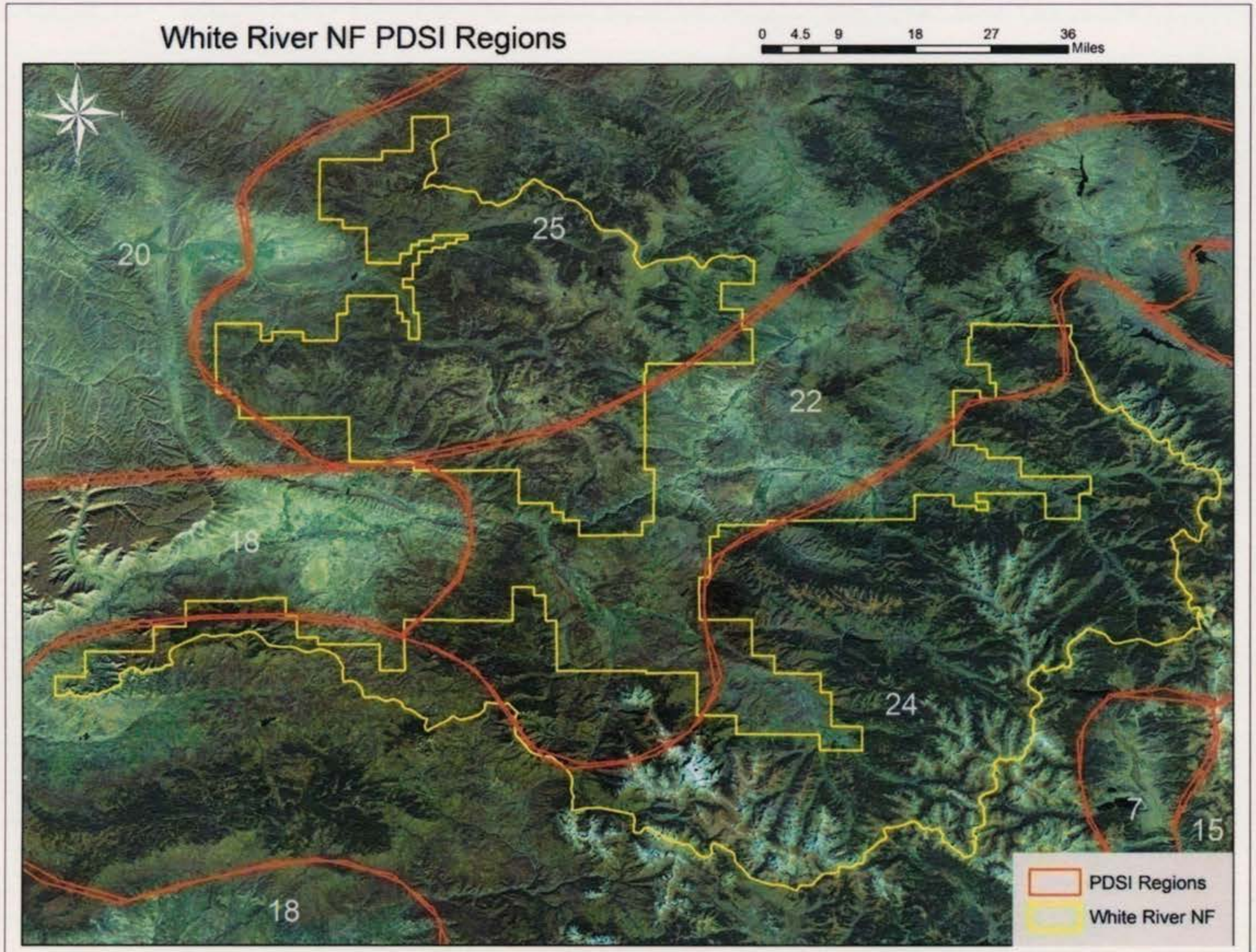

White River NF PDSI Regions
0
4.5
9
18
27
36
Miles
20
25
22
18
24
7
15
18
PDSI Regions
White River NF

Figure C8. Region 25 – Northern Rocky Mountain, CO. Palmer Modified Drought Index (1950-2008; Colorado Climate Center)

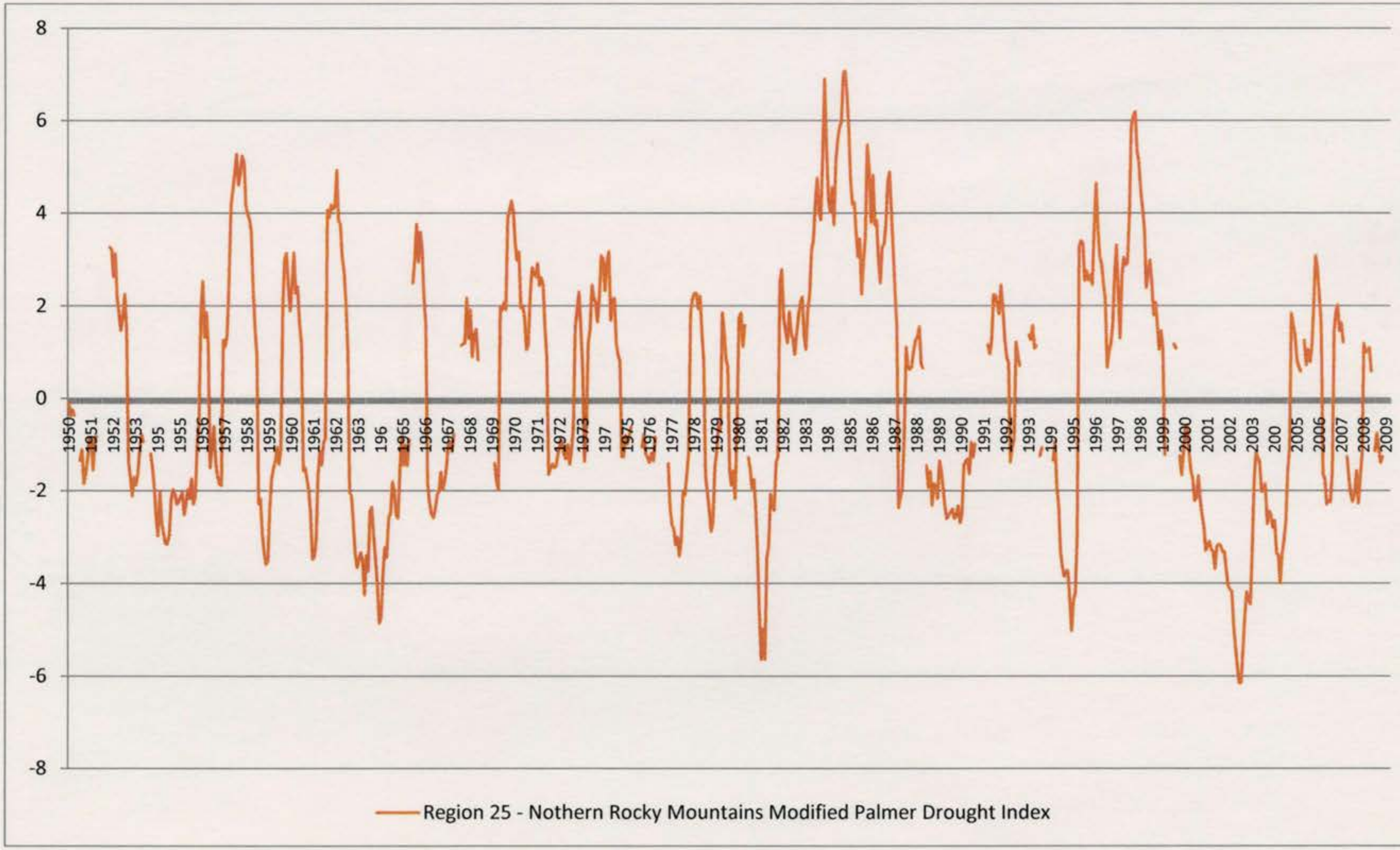


Figure C9. Region 24 – Northern Rocky Mountain, CO. Palmer Modified Drought Index (1950-2008; Colorado Climate Center)

Figure C10. Annual maximum and minimum Palmer Modified Drought Index (Colorado Climate Center) for Colorado Regions 24 and 25.

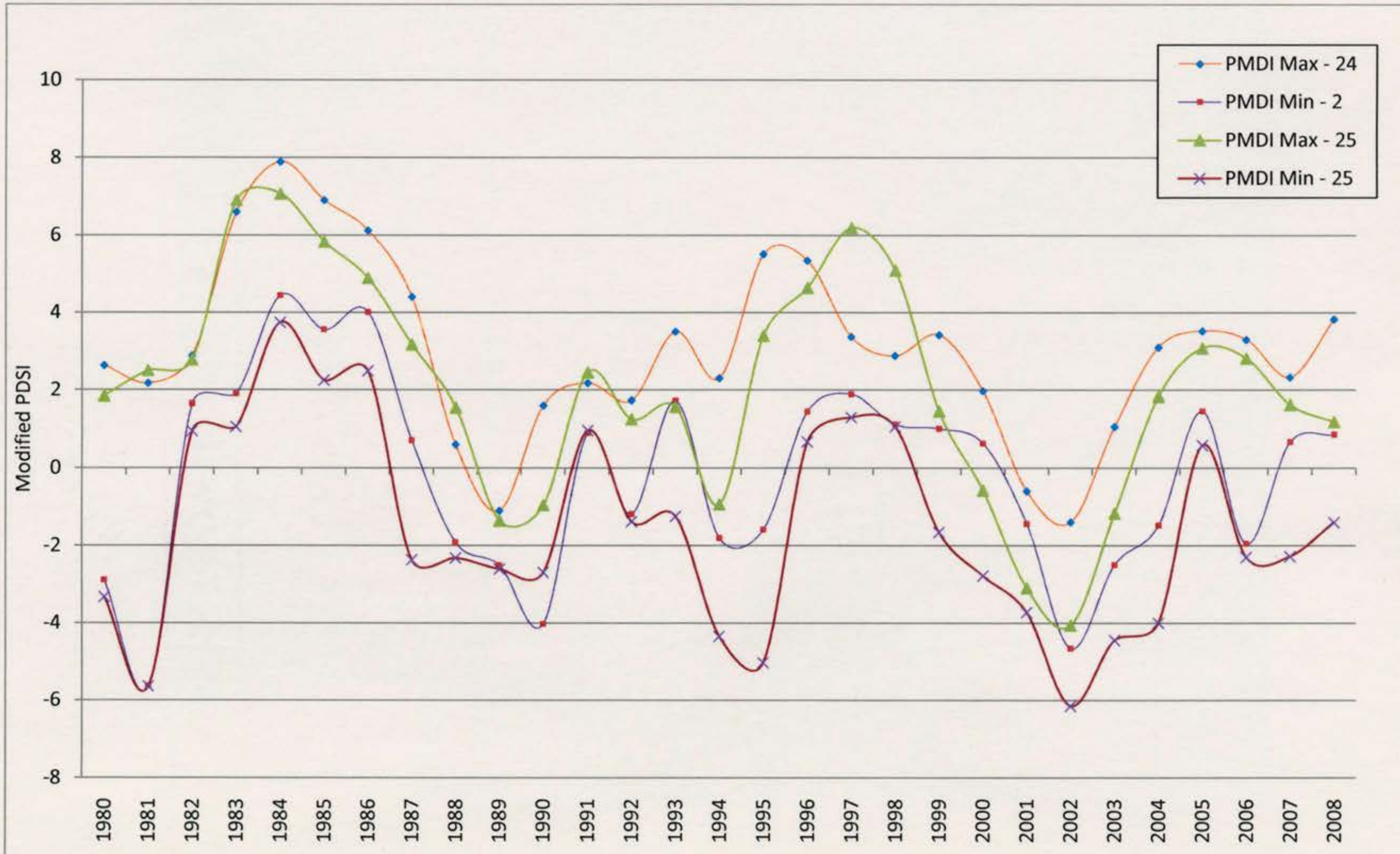


Figure C11. Field assessed fire points on the Arapaho National Forest, CO. with USDA Forest Service Region 2 Aerial Detection Survey mountain pine beetle-caused lodgepole pine mortality (1980-1987).

Arapaho NF Field Assessed Fire Points

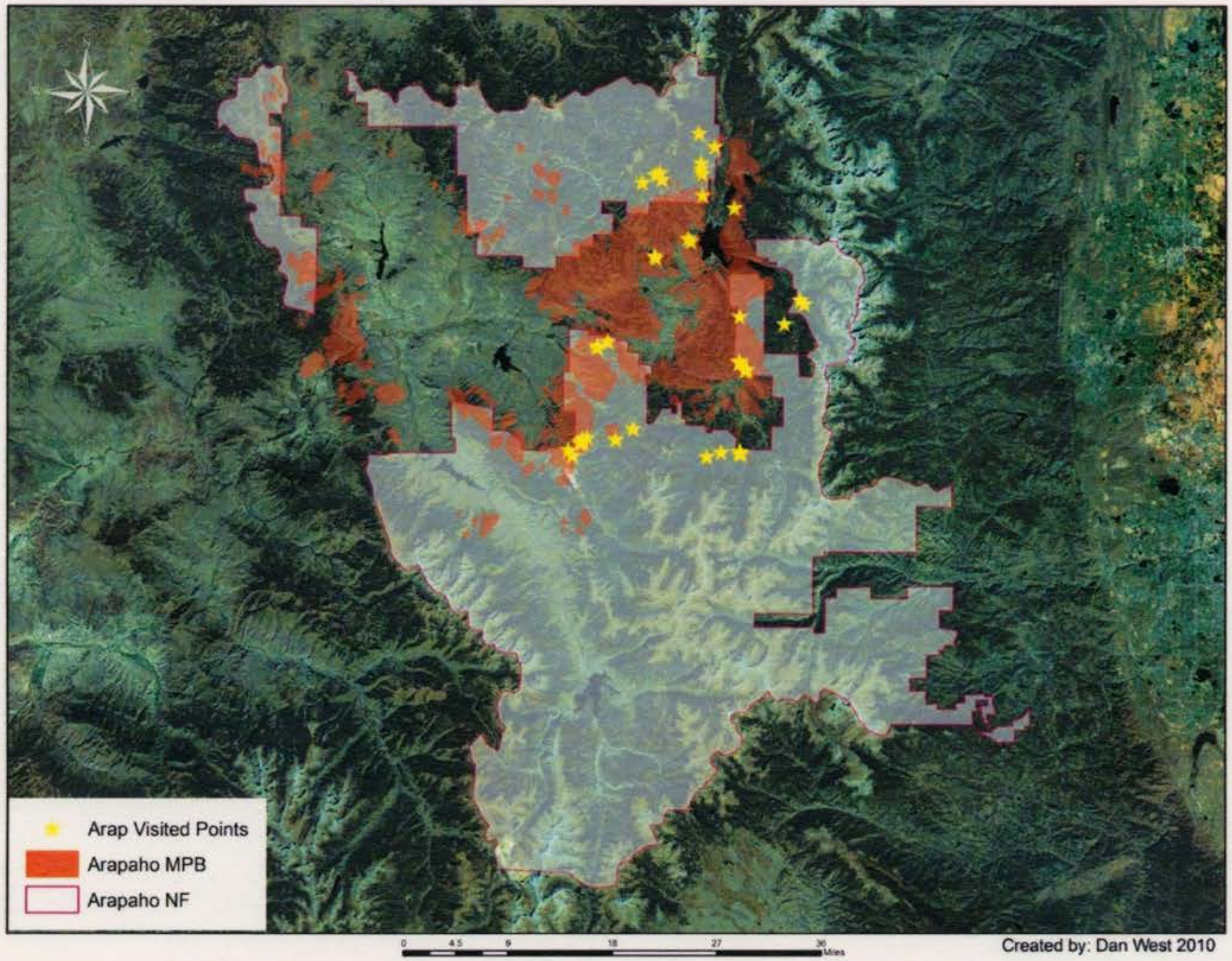


Figure C12. Field assessed fire points on the White River National Forest, CO. with USDA Forest Service, Region 2 Aerial Detection Survey mountain pine beetle-caused lodgepole pine mortality (1981-1987).

White River NF Field Assessed Fire Points

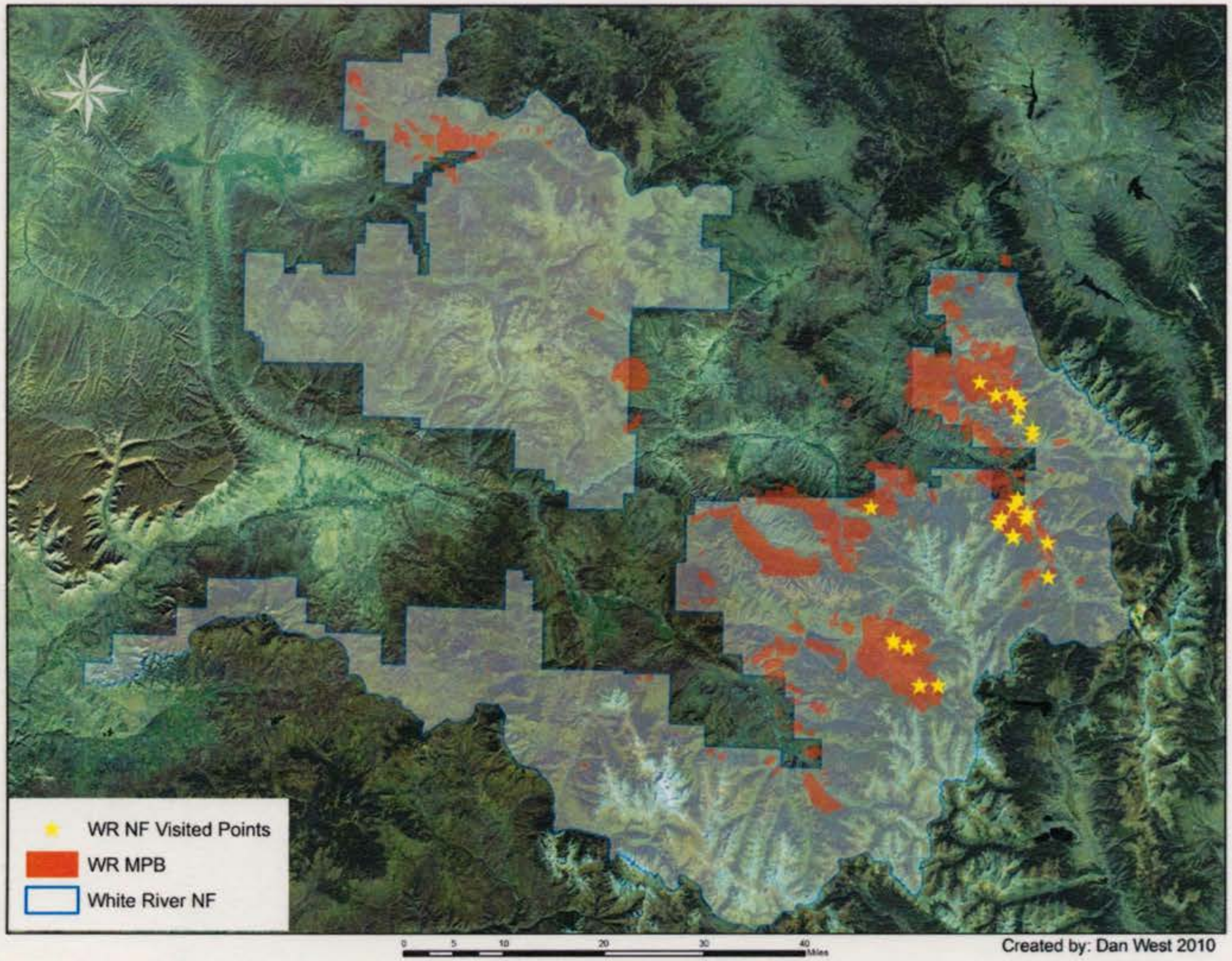


Figure C13. Arapaho National Forest inventoried stands (RMRIS: 1978-1994) intersecting mountain pine beetle-caused lodgepole pine mortality (1980-1987).

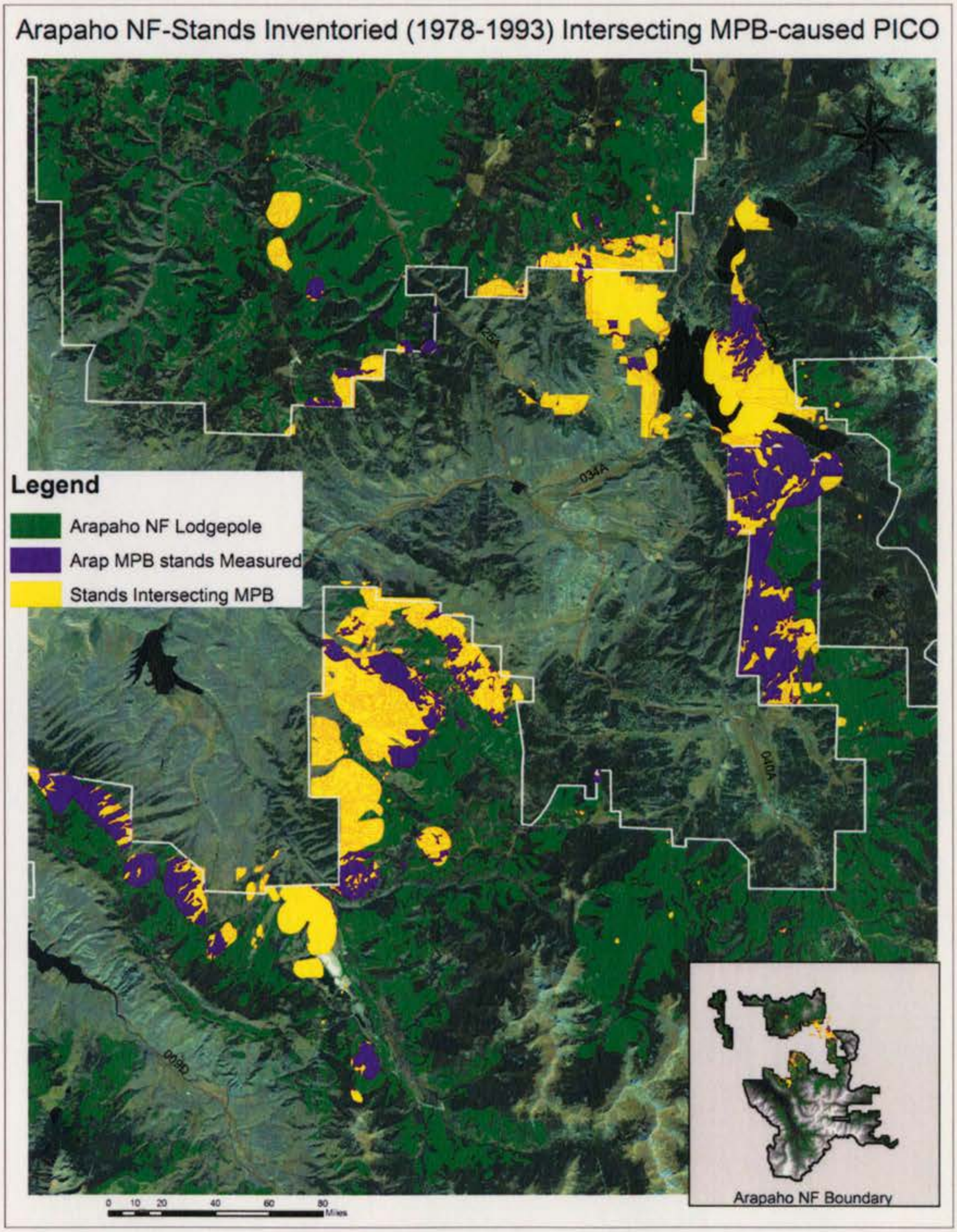


Figure C14. White River National Forest inventoried stands (RMRIS: 1978-1994) intersecting USDA Forest Service, Region 2, Aerial Detection Survey mountain pine beetle-caused lodgepole pine mortality (1981-1987).

White River NF-Stands Inventoried (1978-1993) Intersecting ADS MPB-caused PICO mortality

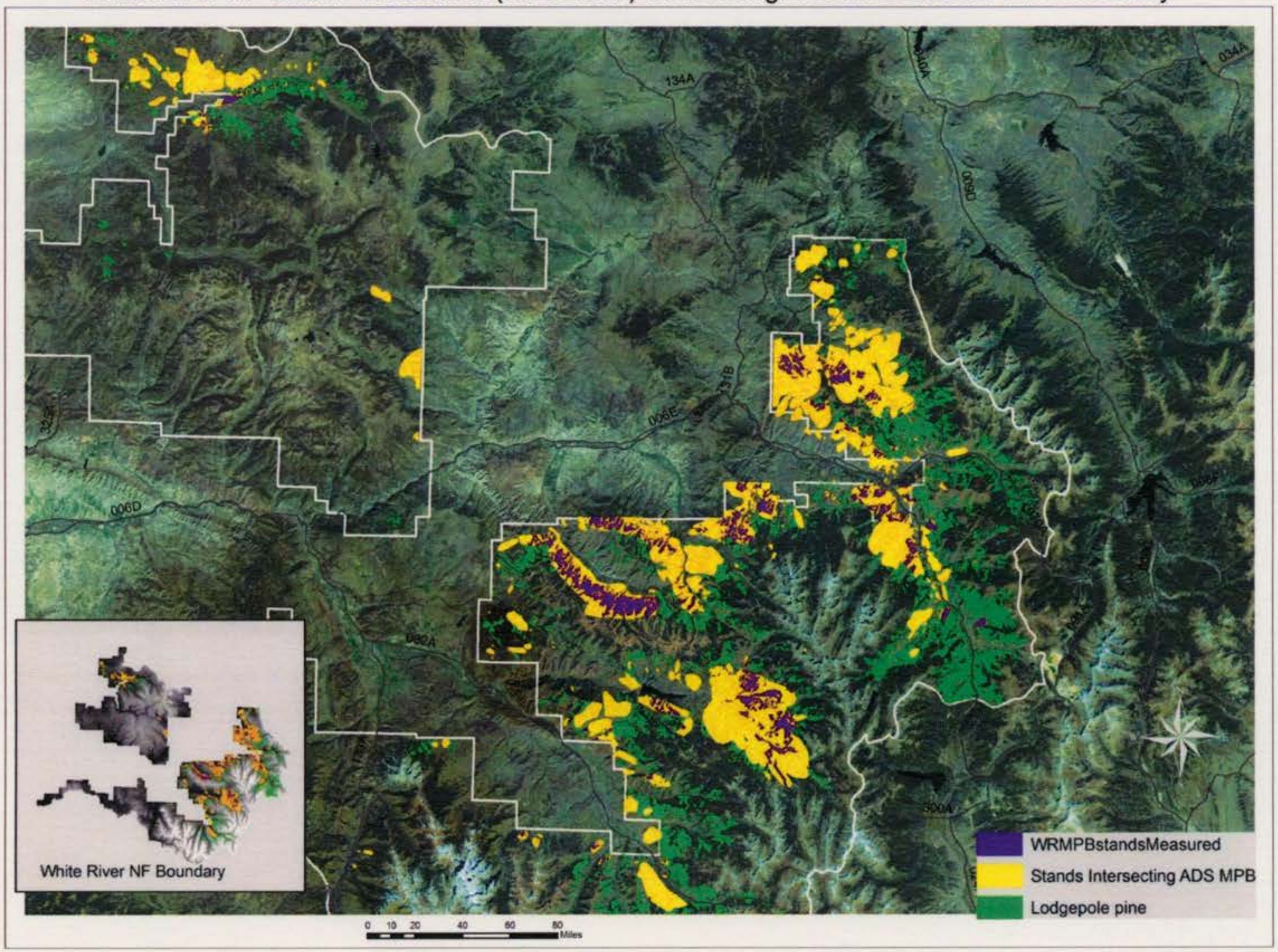
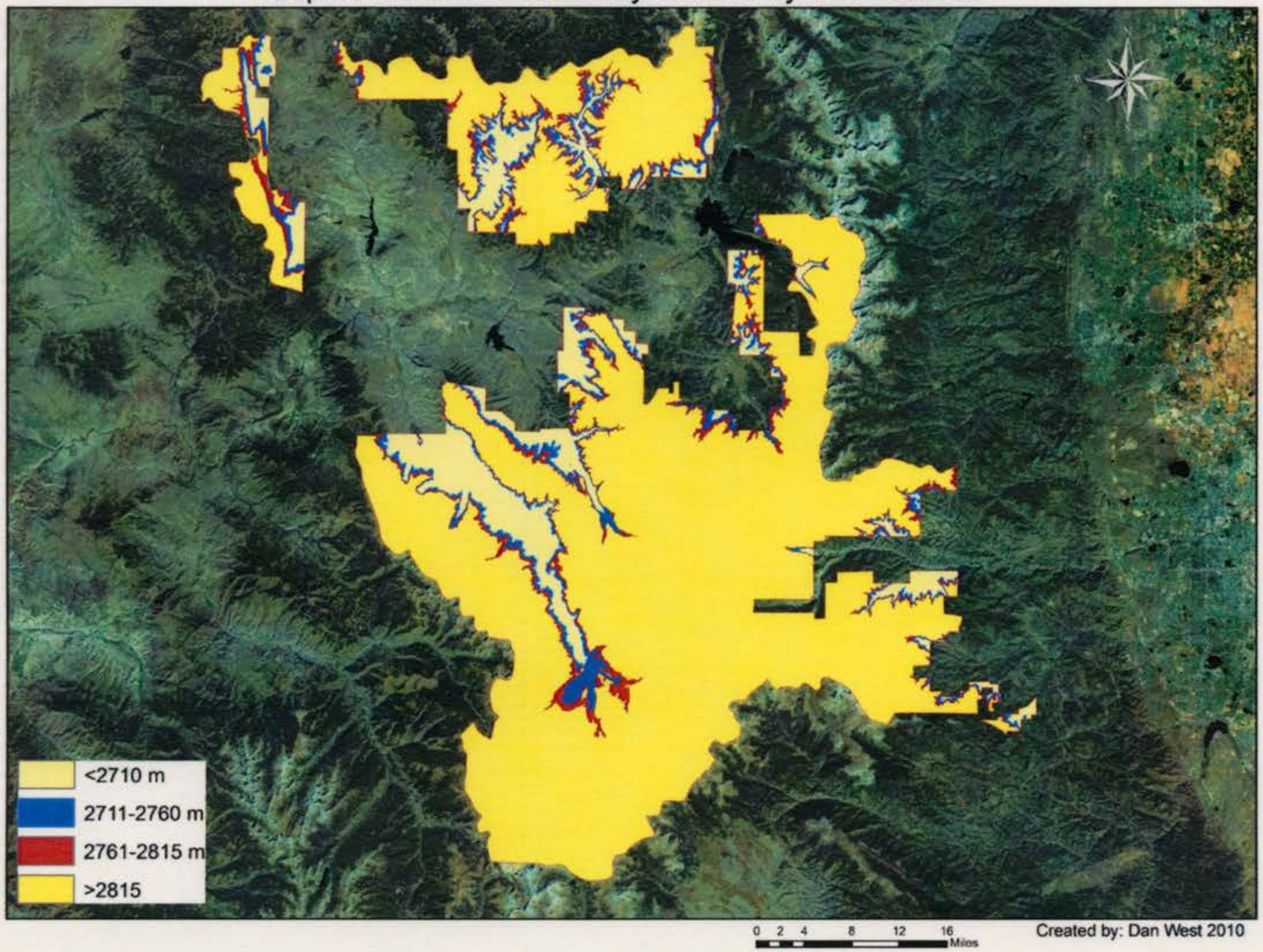


Figure C15. Arapaho National Forest probability surface of lightning-caused ignitions occurring with 1980's USDA Forest Service Region 2, mountain pine beetle-caused lodgepole pine mortality across the entire forest.

Arapaho NF Joint Probability Surface by CDF Quartile



Created by: Dan West 2010

Figure C16. White River National Forest joint probability surface of lightning-caused ignitions occurring with USDA Forest Service Region 2, 1980's mountain pine beetle-caused lodgepole pine mortality across the entire forest.

White River NF Joint Probability Surface by CDF Quartile