



**Using the Landscape Assessment System (LAS) to Assess
Mountain Pine Beetle-Caused Mortality of Whitebark Pine,
Greater Yellowstone Ecosystem, 2009:
Project Report**

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Executive Summary

This report presents the results of an aerial survey conducted in the summer of 2009 to assess mountain pine beetle (*Dendroctonus ponderosae*)-caused mortality in Greater Yellowstone Ecosystem (GYE) whitebark pine (*Pinus albicaulis*) forests (850,000 ha). We used the Landscape Assessment System (LAS), an innovative aerial survey method that uses a unique combination of low-flying airplane over-flights (600-800 m above ground level) in conjunction with geo-tagged oblique aerial photography to assess the cumulative mortality at the sub-watershed level. The project consisted of 8,673 km of flightlines, along which 4,653 aerial photos were captured at the sub-watershed level. Each photo was classified based on the Mountain Pine Beetle-caused Mortality Rating System (0-6). Mortality maps were generated using four different spatial datasets: (1) aerial photos (look-at points); (2) sub-watersheds; (3) the GYE whitebark pine distribution, and (4) an interpolated mortality surface for non-sampled areas. Look-at point maps were generated by symbolizing the points by the appropriate mortality values. Sub-watershed maps were generated by “spatially joining” look-at points and sub-watersheds that share a location. The whitebark pine distribution maps were generated by “clipping” the sub-watershed polygons to the distribution layer to provide a delineation of whitebark pine within each sub-watershed. In sub-watersheds not sampled by look-at points, a mortality surface was interpolated. A total of 2,528 sub-watersheds (73% by area) were sampled with aerial photos. Results that combine sampled and interpolated mortality values (27% by area) indicate that 46% of GYE whitebark pine distribution showed high mortality (class 3-6), 36% showed medium mortality (2-2.9), 13% showed low mortality (1), and 5% showed no unusual mountain pine beetle-caused mortality (0). The maps and spatial data show mortality levels that are distinctly related to geographic location and associated landscape attributes; they provide the precise locations of forests that still remain as fully functioning ecosystems with living, mature, cone-bearing trees, along with the location and extent of forests with high, medium and low levels of mortality. This spatially explicit mortality information is intended to help forest managers develop and implement conservation strategies that include both preservation and restoration efforts.

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Introduction

Across the Greater Yellowstone Ecosystem (GYE), an important component of the ecosystem is facing serious decline. The high-elevation whitebark pine (*Pinus albicaulis*) forests are experiencing heavy mortality in many areas as a result of both natural and human-induced factors (Gibson et al. 2008). The principal agents in this decline are epidemics of mountain pine beetle (*Dendroctonus ponderosae*), and the introduced disease white pine blister rust (*Cronartium ribicola*). This mortality was largely unexpected. Under historic climate regimes, these areas were too cold for the beetle to thrive. Although past tree mortality did occasionally occur during periods of unusually warm weather (e.g., the 1930s and 1970's), these outbreaks were short-lived and limited in scale. Unfortunately, with the level of anthropogenic climate warming that has already occurred, the harsh conditions that served to protect these forests have become increasingly rare. As a consequence, significant mountain pine beetle-caused mortality is taking place year after year.

Since 2000, studies have documented an alarming level of mountain pine beetle-caused mortality throughout GYE whitebark pine (Logan and Powell 2001, USDA 2004, Gibson 2006). However, these studies have lacked data quantifying the full spatial extent and intensity of these outbreaks. The study described herein is a comprehensive landscape-level evaluation of the current status and condition of whitebark pine in the GYE. The approach we developed evaluates and documents, with geo-tagged oblique aerial photography and spatial data, the cumulative impacts of mountain pine beetle-caused mortality of the whitebark pine forests throughout the entire GYE.

The Greater Yellowstone Ecosystem

Although the GYE is an informal designation, the currently accepted boundaries include approximately 8,093,712 ha (20,000,000 ac), an area roughly the size of South Carolina. It is generally recognized that the GYE is one of the last remaining large, nearly intact ecosystems of the earth's northern temperate region. This mountainous landscape is administratively complex, containing portions of three states, including south-central Montana, northwest Wyoming and southeast Idaho; two national parks and six national forests, including Yellowstone National Park, Grand Teton National Park, Shoshone National Forest (Region-2), Beaverhead-Deerlodge, Gallatin and Custer National Forests (Region-1) and Bridger-Teton and Caribou-Targhee National Forests (Region-4); along with two national wildlife refuges and various state administrative units. The administrative complexity is matched by the complex geography of this ecosystem, which includes 21 major mountain ranges. Geographic complexity is reflected in climate, weather, and resulting plant and animal communities. The high-elevation five-needle pine forests serve as an integrating factor across this diverse, heterogeneous landscape.

The high mountains of the GYE are home to extensive stands of five-needle pines. Because the range of limber pine (*Pinus flexilis*) partially overlaps that of whitebark pine, and because they are so similar in appearance, we do not attempt to distinguish between these two species in this study. Arno and Hoff 1989 found that whitebark pine distribution is heavily controlled by elevation; whitebark pine can occupy nearly pure homogeneous stands in harsh, dry mountainous terrain, although it typically co-exists with other conifers in moister and more

protected high-elevation sites. High elevation is a relative concept. In the southern GYE, high elevation may start around 2,700 m, whereas in the northern GYE, 2,500 m would be considered high elevation. For this study, we use a 2,500 m contour to delineate the lower limits of whitebark pine throughout the GYE.

Whitebark pine forests of the GYE grow in a myriad of shapes, from twisted and stunted to tall and wide. They occur in four distinct settings:

1. Subalpine sites of mixed conifer forests where whitebark pine is a minor component.
2. Upper subalpine sites where whitebark pine is a major species but is successional replaced by shade-tolerant fir or spruce.
3. Upper subalpine sites where whitebark pine is the dominant tree species able to successfully reproduce and mature. These are typically dry, cold slopes, where trees often occur in clumps with multiple leaders, small groves or tree islands.
4. At treeline in areas such as the Beartooth Plateau where vast expanses of dwarf/Krummholz whitebark pine forests exist.

In 2008 the Greater Yellowstone Whitebark Pine Committee (GYWPC) used USDA Forest Service and National Park Service vegetation data to derive a Greater Yellowstone Area (GYA) whitebark pine distribution map. This map encompasses approximately 850,000 ha and was used as the study area boundary within the GYA; an existing USGS distribution map was used for areas outside the GYA but within the GYE (Figure 1). The GYA includes only state and federally administered lands, while the GYE boundary additionally includes private and tribal lands.

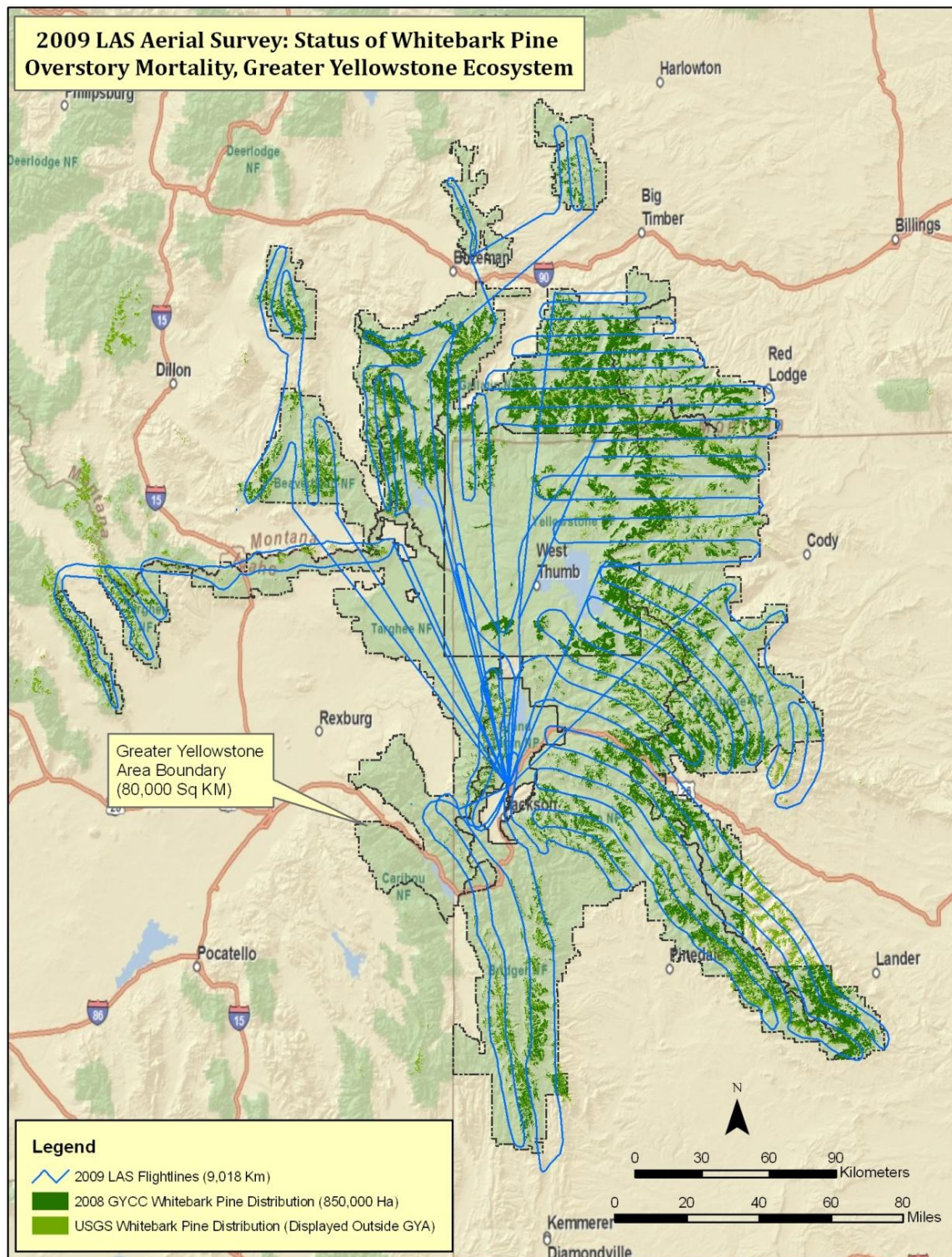


Figure 1. Map of the GYE showing flightlines and project area.

Ecological importance of whitebark pine

Effective monitoring of whitebark pine mortality is a critical component to forest management because of the ecological services that this important species provides. Whitebark pine plays a major role in the ecological integrity of the GYE since it functions as both a foundation and a keystone species. It forms the foundation of high mountain and alpine ecosystems by providing the major biomass and primary productivity, enhancing soil formation, and serving as "nurse trees" for subalpine fir (Lanner 1996). In the larger spatial context of the entire GYE, it is a keystone species because these forests are crucial for distribution of winter snow and attenuation of snow-melt water release in the spring. Peak stream-flow would occur earlier and be of shorter duration without the protective shading provided by whitebark pine. Altered hydrology has important implications for cold-water fisheries as well as human uses of water. Early and spiked spring flow translates into a greater likelihood of dangerously reduced flow and lethal high temperatures later in the summer. Whitebark pine is a species whose loss would reverberate through the entire Rocky Mountain ecosystem, resulting in impacts that far outweigh its physical presence on the landscape (Tomback et al. 2001, Ellison et al. 2005, and Logan et al. 2008).

The mutualistic relationship between whitebark pine and Clark's nutcracker (*Nucifraga columbiana*) is well documented. Since whitebark pine depends almost exclusively on the Clark's nutcracker for natural regeneration (Tomback 2001), the loss of most mature whitebark pines in a stand may result in no future regeneration if the residual live trees cannot support a nutcracker population.

Whitebark pine also provides critical wildlife amenities. Its large, fleshy, highly nutritious seeds also provide an important food resource for a wide array of other wildlife ranging from the red squirrel (*Tamiasciurus hudsonicus*) to the grizzly bear (*Ursus arctos horribilis*). The importance of whitebark pine seeds to grizzly bear is of particular importance in the GYE due to scarcity of other high quality food during the critical time prior to entering hibernation (Mattson et al. 1992, Mattson 2000). Grizzly bears feed on vast quantities of whitebark pine cones that have been collected by red squirrels and stored in middens that are readily available to foraging bears (Mattson and Reinhart 1997). When grizzly bears feed on pine seeds in the GYE, they feed on virtually nothing else (Mattson et al. 1991, Mattson and Reinhart 1994). Fat from these seeds is efficiently converted to body fat and promotes successful reproduction of female grizzly bears, which rely on body fat reserves not only for hibernation, but also to support lactation (Hellgren 1998).

There is a strong relationship between whitebark pine seed crop size and grizzly bear demography in the GYE. During years when pine seeds are scarce, conflicts with humans escalate dramatically, as does the death rate among bears (Blanchard 1990, Mattson et al. 1992, Blanchard and Knight 1995, Schwartz et al. 2006). Conversely, during years when Yellowstone's grizzly bears are intensively using pine seeds, conflicts with humans decrease and the bear population increases (Pease and Mattson 1999, Schwartz et al. 2006). Essentially, when bears are feeding in the remote habitat of the whitebark pine, they are out of harm's way; conversely, during years of low cone production, bears are much more likely to come into conflict with humans, with consequently higher mortality rates.

The impact of the mountain pine beetle and global warming on whitebark pine

The mountain pine beetle is a native insect that plays an important ecological role in disturbance-maintained forests such as lodgepole pine (*Pinus contorta*). Mountain pine beetles feed and reproduce under the bark of their host tree, ultimately killing the infested tree.

Without disturbances such as mountain pine beetle outbreaks and fire, lodgepole would be replaced over much of its range by shade-tolerant spruce and fir. Historically, the range of mountain pine beetle was limited to lower elevation forests because of the unfavorable climatic conditions found at higher elevations. For this reason, whitebark pine forests, which are located above approximately 2,500 m in elevation in the GYE, have largely avoided past mountain pine beetle outbreaks. With the recent advent of anthropogenic global warming, the ecological relationship between mountain pine beetle and whitebark pine has undergone a fundamental shift. The harsh environment that served to protect these forests has moderated to the extent that it is no longer a deterrent to outbreak populations of beetles; as a result, an alarming number of mountain pine beetle outbreaks are taking place in previously inhospitable whitebark pine forests.

Weather, as an expression of climate, has two important effects on mountain pine beetle outbreak potential. Historical winter temperatures in whitebark pine habitats were frequently cold enough to kill mountain pine beetle life stages in all but the most protected sites, such as tree boles beneath insulating snow cover. Summer temperatures typically did not provide enough heat increment for the beetle to complete an entire life cycle in one year (univoltinism). The combination of cold temperature, winter mortality, and cool summer

temperatures served to keep mountain pine beetle populations in check. With the advent of a warming climate, winter temperatures have become mild enough to allow substantial overwinter survival of all life stages, and summer thermal energy is sufficient for the beetle to complete an entire life cycle in one year.

In historical climates these necessary conditions occurred simultaneously only infrequently. With the level of warming that has already occurred, their simultaneous occurrence has become common. Although evidence indicates past outbreaks of mountain pine beetle in whitebark pine associated with brief warm periods, nothing like the current level of mortality exists in the historical record. Whitebark pine ecosystems appear to be particularly vulnerable to mountain pine beetle outbreaks because they have not coevolved with mountain pine beetle in the same manner as lower-elevation forest ecosystems like lodgepole pine forests. The lack of co evolution may be influencing the heavy mountain pine beetle-caused mortality suffered by whitebark pine.

Aerial Detection Survey (ADS): The traditional forest health monitoring method

The USDA Forest Service Forest Health Protection (FHP) and its state cooperating partners have been conducting aerial detection surveys (ADS) for over 50 years (McConnell and Avila 2004). ADS has become the standard method of tracking forest health across large landscapes. These overview surveys provide essential information on insect and disease occurrence and other forest disturbance agents, and provide cost-effective and timely reporting, enabling managers to respond to changing forest health conditions and trends (McConnell and Avila 2004). ADS methods utilize low-level flights, typically 300 to 600 meters

above ground level, to map forest damage. Observers use either digital or paper maps, typically 1:100,000-scale, upon which they record forest damage by drawing points and polygons attributed by damage type, defoliation intensity or number of dead trees. This technique is called sketch mapping. In general, ADS sketch mapping evaluates and maps annual mortality and decline of all tree species from all insects and diseases in a given area.

Recent ADS data have documented a considerable increase in mountain pine beetle-related mortality throughout the Intermountain West (Gibson 2006, Gibson et al. 2008 and Kegley et al. 2004). However, the ADS coverage is not always complete or regular, and surveys only record the previous year's mortality; therefore cumulative mortality is known only if the same areas are flown year after year. Moreover, ADS provides little information regarding what the residual stands "look like" following an outbreak; so even in areas where annual mortality levels have been recorded, it is difficult to determine the amount of live whitebark pine remaining to provide regeneration potential (Schwandt and Kegley 2008). Notwithstanding the limitations of annual ADS data, they still provide very useful information on mortality trends. We used existing ADS annual survey data to map the occurrence of mountain pine beetle-caused mortality between 1999- 2008 (Figures 2 and 3). It is important to note that these maps reflect only the occurrence of beetle-caused mortality, not mortality intensity, because ADS data does not consistently record mortality intensity.

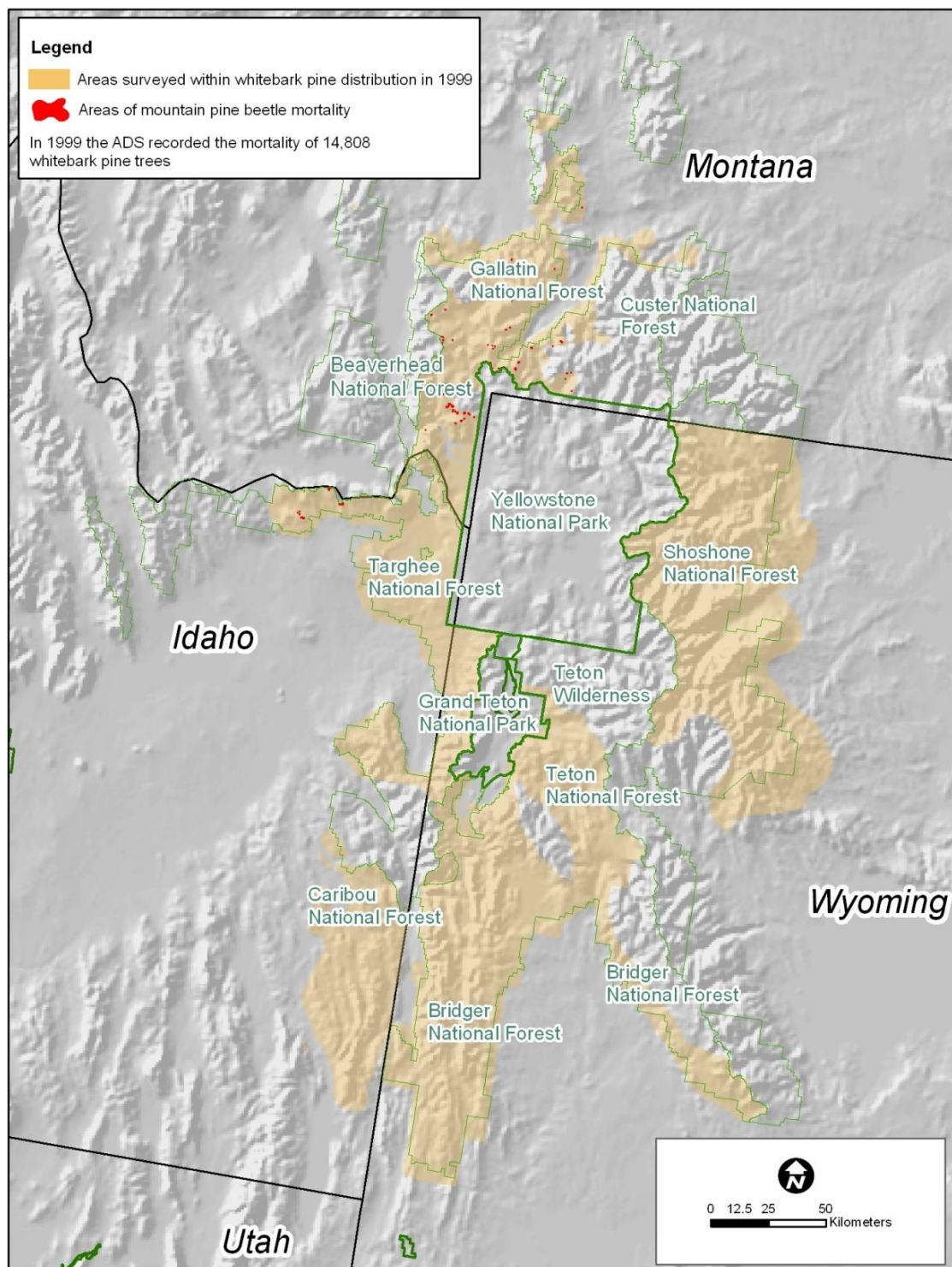


Figure 2. 1999 ADS mountain pine beetle-caused whitebark pine mortality.

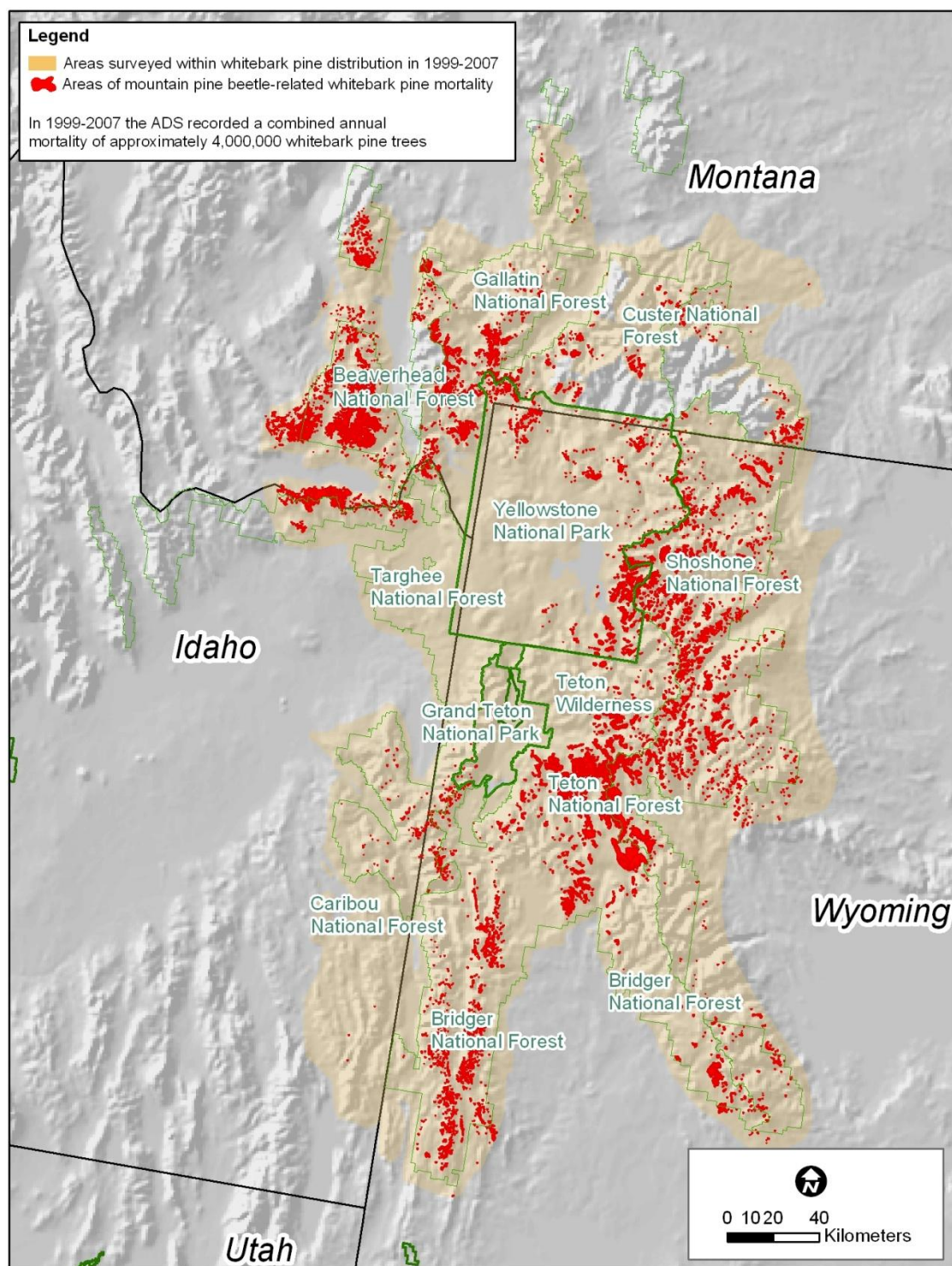


Figure 3. 1999-2007 (combined) ADS mountain pine beetle-caused whitebark pine mortality.

Remote Sensing Application Center (RSAC) canopy change detection data

In 2008, the Remote Sensing Application Center (RSAC) used Landsat satellite imagery to detect canopy change in all conifer forests, using scenes from 2000, 2007 and 2008 across approximately 90 percent of the GYE (Goetz et al. 2009). Whitebark pine mortality was isolated using the GYCC Whitebark Pine Distribution layer as a mask. Canopy change data did not provide information specific to mortality levels (i.e., how much is dead or alive); rather they showed change that was assumed to be related to mortality. The resulting whitebark pine canopy change layer showed low, moderate and high change in canopy estimates, which were used as surrogates for whitebark pine mortality. Also worth noting is that the canopy change detection did not capture whitebark pine mortality that occurred prior to 2000 in areas such as the Centennial, Gravelly and southeast Absaroka mountain ranges. The GYWPC used the RSAC canopy change data to estimate mortality as part of their condition assessment tool.

Methods

Using an aerial survey approach to assess mountain pine beetle-caused whitebark pine mortality is effective because:

1. During the summer following successful beetle attacks, bright red foliage is clearly visible from aircraft and easily captured with photography (Figure 4a).
2. Five-needle pines have distinctive rounded and irregularly spreading crowns that are easily recognized and distinguished from most other conifers without extensive training (Figure 4b). There are notable exceptions, however, that

include whitebark pine being mistaken for Douglas fir (*Pseudotsuga menziesii*) and vice versa, as well as single-stem whitebark pine being mistaken for open-stand lodgepole pine. These exceptions require the observer to more thoroughly examine the photography and consult with local foresters to delineate the distribution of whitebark pine forests.

3. In the aftermath of an outbreak, beetle-killed trees can be distinguished from fire-killed trees because the fine material remains on the beetle-killed tree, giving it a distinct appearance (Figure 4c).



Figure 4a. Red canopy of infested whitebark pine clearly captured with aerial photography.



Figure 4b. Rounded and irregularly spreading crowns indicative of whitebark pine.



Figure 4c. Left-side of photo shows whitebark pine killed by beetles (fine material remains on trees). Right-side of photo shows trees killed by fire (no fine material).

The Landscape Assessment System (LAS): An innovative aerial survey method

In 2006-2007, we developed the Landscape Assessment System (LAS), an aerial survey method, to monitor the extent and intensity of cumulative beetle-caused mortality in whitebark pine forests across large and remote mountainous areas. In the summer of 2008, we tested the LAS method in 5 pilot areas across the GYE (approximately 20 percent of the GYE whitebark pine was sampled). The pilot study showed very similar mortality trends to those recorded by ADS in 2008. We determined that LAS provided an effective and relatively inexpensive way to inventory and assess beetle-caused mortality in whitebark pine forests (Logan et al. 2008). In 2009, we entered into a contract with the USDA Forest Service to use the LAS method to conduct a GYE-wide assessment of mountain pine beetle-caused mortality in whitebark pine forests.

The LAS aerial survey method uses a unique combination of low-flying airplane over-flights (600-800 m above ground level), in conjunction with geo-tagged oblique aerial photography, to assess the cumulative mortality in either active mountain pine beetle outbreaks or post-outbreak forests. The post-outbreak forests are referred to as residual forests and are identified as gray forests with no evidence of active beetle activity (red trees). This assessment is done by experienced observers who visually examine beetle-caused mortality on a photo-by-photo basis and assign a numeric rating of 0-6 based on a Mountain Pine Beetle-caused Mortality Rating System (Appendix A). The system ranks whitebark pine mortality intensity based on the amount and intensity of mountain pine beetle activity visible in the photograph.

In forests with active outbreaks, the amount of red (recent attack) and gray (old attack) whitebark pine overstory is visually assessed and rated. The active outbreak ratings range from 0-4. A mortality rating of 0 (zero) represents a landscape with no unusual mountain pine beetle activity. No unusual activity refers to landscapes that may contain an occasional red tree, but there is no evidence of mortality expanding to neighboring trees. A mortality rating of 1 (one) indicates a landscape with the occasional spots of red trees, but the spots do not show evidence of multi-year activity. A mortality rating of 2 (two) represents a landscape with multiple spots of red and gray trees that show two or more years of subsequent mortality. A mortality rating of 3 (three) indicates an active widespread outbreak, with coalesced spots of red and gray trees across the landscape. A mortality rating of 4 (four) represents a landscape where red and grey spots have completely coalesced, indicating that essentially the entire whitebark pine overstory has been killed.

In areas where the outbreak cycle has been completed, we refer to these forests as residual forests, ratings from 5 (five) through 6 (six) are used, depending upon the amount of remaining green whitebark pine overstory visible on the landscape. Mortality ratings of 5, 5.25, 5.5, and 5.75 indicate a decreasing amount of green overstory remaining on the landscape. A mortality rating of 6 (six) represents a gray forest where essentially the entire green whitebark pine overstory has been removed (Figure 5).

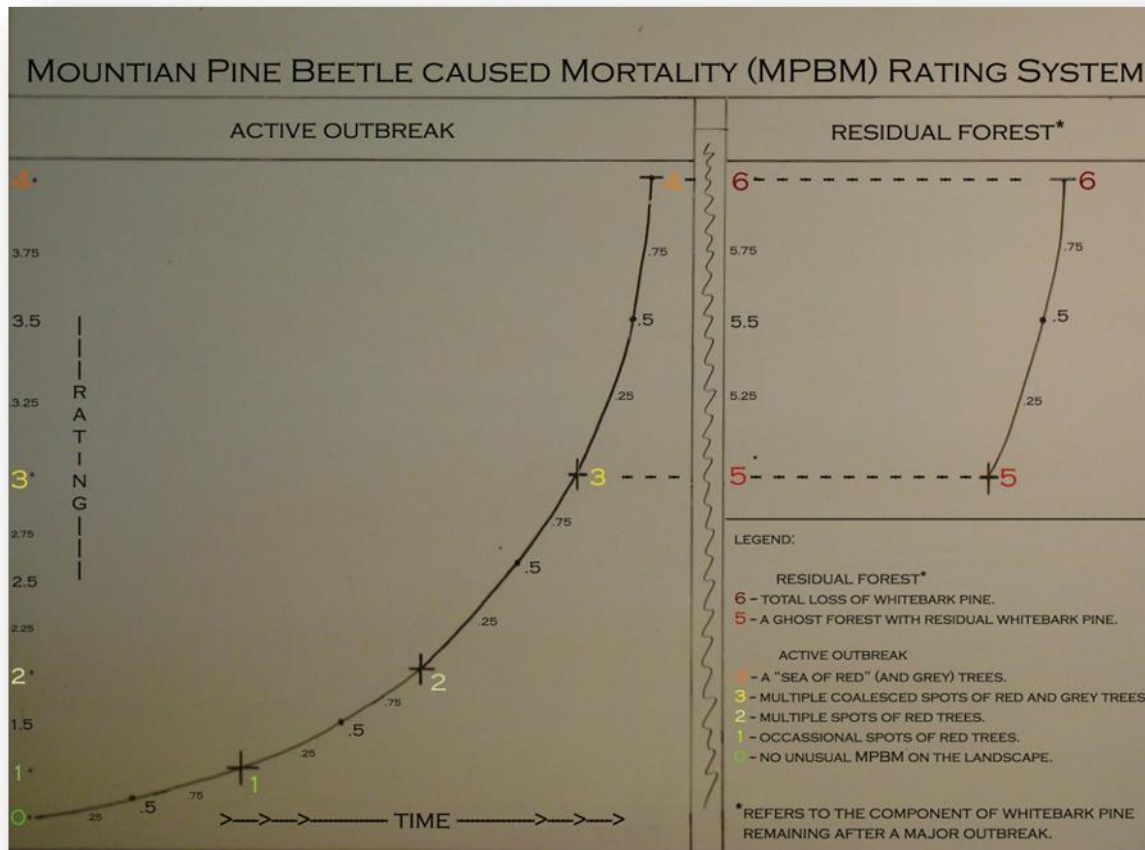


Figure 5. Graphical representation of the MPBM Rating System.

This graph represents both active outbreaks and residual forests remaining after a major outbreak. The active outbreak arc is shown on the left and tracks outbreak intensity over time, from category 0 to category 4. Outbreaks do not necessarily follow the full arc displayed in the graph. In fact, our research indicates that most outbreaks in the GYE end at a category 3, 3.25, 3.5, or 3.75 instead of a category 4. The residual forest arc is shown on the right and indicates the residual forest condition after the outbreak has ended (i.e., no visible red trees remain on the landscape), with ranges from category 5 to category 6. The graph shows the direct relationship between active outbreak categories and residual forest categories. For example, an

active outbreak that ends at a category 3 becomes a category 5 once all the red trees have turned gray. Major active outbreaks are classified by increasing mortality intensity with ratings of 3, 3.25, 3.5, 3.75 and 4. Residual forests are assigned ratings of 5, 5.25, 5.5, 5.75 and 6, based on the decreasing amount of green overstory that remains once the outbreak has ended.

LAS data collection and processing workflow

The LAS collection and data processing workflow consists of eight steps: (1) flightline development; 2) flight scheduling; 3) aerial data collection; (4) data transfer/data examination; (5) “snapshot view” generation; (6) photo evaluation/mortality ratings assessment; (7) mortality map generation; and (8) ground verification.

- 1. Flightline development.** For this project, flightlines were developed within Google Earth using the GYWPC and USGS whitebark pine distribution maps and the 2500 m contour as background layers to ensure complete spatial coverage. A system of parallel flightlines was developed, using a fixed interval of 8 km (Figure 1). This interval was used because our 2008 LAS pilot study revealed that about a 4 to 5 km photo width was optimal. Therefore, with an observer on each side of the plane, an 8 km interval translates into each observer being able to capture a 4 km swath of forest on his/her respective side of the plane. Flightlines were also developed to run parallel to mountains ridges instead of over the crest of these ridges, allowing for lower flight heights and higher quality imagery. Flightline data were transferred to both an on-board GPS unit, used by the pilot for navigation, and to a handheld GPS unit used by the observers to record flight path information.

- 2. Flight scheduling.** The LAS aerial survey approach uses a flight speed of approximately 85 to 90 knots per hour. The study area consisted of 8,673 km of flightlines. The survey therefore required approximately 55 hrs of flying. The 55 hours were divided into 10 flight days, 5 to 6 hours per day. Our 2009 flight days were July 6, 7, 13, 15, 16, 17 and August 4, 5, 6 and 7. The Jackson Hole airport was our base of operations, and each flight started and ended there.
- 3. Aerial survey data collection.** The LAS approach uses a two-observer technique with an observer seated on each side of the aircraft, each responsible for photo documenting the whitebark pine mortality visible from his/her position. The observer is not only responsible for capturing the photos, but is also responsible for processing and classifying the photos that he/she captures. Thus the observer applies "hands-on" knowledge, gained from observing the landscape from the air, during the post-processing step of classifying whitebark pine mortality. For this study, photos were taken to capture mortality at a sub-watershed scale. Sub-watersheds have discrete geographic boundaries delineated by ridgelines, which form natural breaks that are easily recognized from an aerial perspective. Sub-watersheds (Hydrologic Unit Code 12 (HUC 12)) were delineated using ESRI ArcGIS 9.3 that included a digital elevation model for the GYE. The size of the resulting sub-watersheds ranged from 100 to 800 ha in steep mountainous terrain of the GYE. Subwatersheds ranged from 800 ha to as large as 3000 ha in the flatter portions of the GYE. There were a total of 4,436 sub-watersheds that

intersect with the GYCC whitebark pine distribution map. The sub-watershed polygon layer formed the Minimum Mapping Unit (MMU) for the mapping effort.

- 4. Data Transfer/Data Examination.** After each flight, the photos captured on that flight were transferred from the camera to a hard drive in both high-quality Jpeg and Raw format. Within Picasa (www.picasa.google.com), an image viewing program, each photo was examined for image quality, and dark shadows were removed using a standard image enhancement technique. Then, using RoboGeo (www.robogeo.com), the flight path and geo-tagged photos were transferred to keyhole markup language (KML) format for use in Google Earth (www.earth.google.com). This processing step generated a point (x, y and z coordinates) which identifies the location of each photo along the flightline. We call these identifiers "photo points." In certain instances in our study, the photos were missing coordinates because the camera's GPS unit temporarily lost satellite reception. As a result these photos were geo-tagged using the track log data collected by the handheld GPS unit. In Google Earth, the flightlines, photo points and linked images were examined for spatial accuracy and spatial coverage on a 3-D globe. All photo point location errors were fixed and/or identified.
- 5. Snapshot view generation.** In Google Earth, the aerial observer re-established a snapshot view, the view that the camera "saw" when the photo was taken. This is a manual process that required zooming to the correct extent and establishing the correct rotational angle of the photo. We used Google Earth to generate latitude and longitude coordinates of the ground location of the snapshot view. We called these "look-at

points,” indicating the point on the ground at which the camera and the observer were looking.

6. Mortality classification. Mortality ratings were assigned during post-processing, using workstations with dual high-definition flat panel monitors. On one monitor, we used Google Earth to display the appropriate KML look-at point file with photo locations and pop-up low-resolution aerial photos. On the other monitor, Picasa displayed the high-resolution aerial photos. Mortality levels were assigned by zooming in to the high resolution photo, visually examining tree mortality, and then applying a single numeric (0-6) rating to each photo based on the (MPBM) Rating System (Appendix A). In Google Earth, each look-at point within the KLM file was assigned the appropriate mortality rating associated with its respective photo.

7. Mortality map generation. Mortality maps for our study were generated using four different spatial data sets: (1) look-at-points; (2) sub-watersheds; (3) the GYE whitebark pine distribution data; and (4) an interpolated mortality surface for non-sampled areas. Look-at point maps were generated by symbolizing the points using the appropriate mortality values and then displaying them on a map. The sub-watershed scale maps were generated by “spatially joining” look-at points and sub-watersheds that shared a location. Thus, mortality information was applied to the spatial extent (ha) of the watershed to form a new GIS layer -- the sub-watershed mortality layer. This layer was attributed by the averaged look-at point mortality values and symbolized using a color ramp, with green indicating no mortality, yellow indicating low mortality, orange

indicating medium mortality, and red indicating high mortality. The GYWPC Whitebark Pine Distribution maps were generated by clipping the sub-watershed mortality layer to the distribution layer to provide a delineation of whitebark pine stands within each sub-watershed. In sub-watersheds and associated GYWPC Whitebark Pine Distribution polygons that were not directly sampled by look-at points, a mortality surface was interpolated using kriging. In such cases the resulting surface provided an estimate of mortality values for the non-sampled polygons.

- 8. Ground verification.** Ground truthing is an important part of any remote sensing study and is necessary to provide an accurate and useful interpretive product (Trude and Clark 2000). A stratified sampling method was used to select transects consisting of existing roads that were relatively accessible and provided access into whitebark pine. Along selected road transects, viewpoints were identified that provided a canopy view similar to the view from an airplane. At these viewpoints the landscape was classified using the MPBM Rating System and compared to the mortality ratings recorded on the aerial photography. Accessible forest stands near these road transects were used for stand-level survey. In these surveys, ecological information was collected that could not be obtained from a remote sensing perspective. Ground verification involved: 1) taking geo-tagged photos to document current conditions, and 2) taking landscape-level photos for comparison with the aerial photo obtained in this project.

Results

Results are presented at the GYE-wide level using four mapping techniques: (1) look-at points; (2) sub-watershed boundaries; (3) interpolated surfaces for non-sampled areas, and (4) whitebark pine distribution level.

GYE-Wide

Look-at point mapping. Over the course of the 2009 LAS project, a total of 6,048 aerial photos were taken. Of these, 4,653 photos were selected for use in the mortality assessment, based on the photo's ability to clearly display sub-watershed whitebark pine mortality. Photos were rejected because of poor image quality, heavy mortality from fire and absence of whitebark pine forests because of either being too low or too high in elevation.

The selected 4,653 geo-tagged aerial photographs collected along 8,673 km of flightlines were visually examined, assessed and assigned a numeric (0-6) rating based on a mortality rating system (Appendix A). Figure 6 shows the frequency distribution of mortality ratings of the aerial photos taken over the course of the project. Figure 7 is a map showing the spatial location of each photo as a look-at point with an associated mortality rating. These maps show the look-at points symbolized by mortality rating (0-6) on a color ramp from green-to-red. The look-at point maps show mortality values at specific point locations and provide a literal representation of landscape conditions at a specified geographic coordinate. However, because these maps are point-based, there is no area (ha) associated with their mortality values.

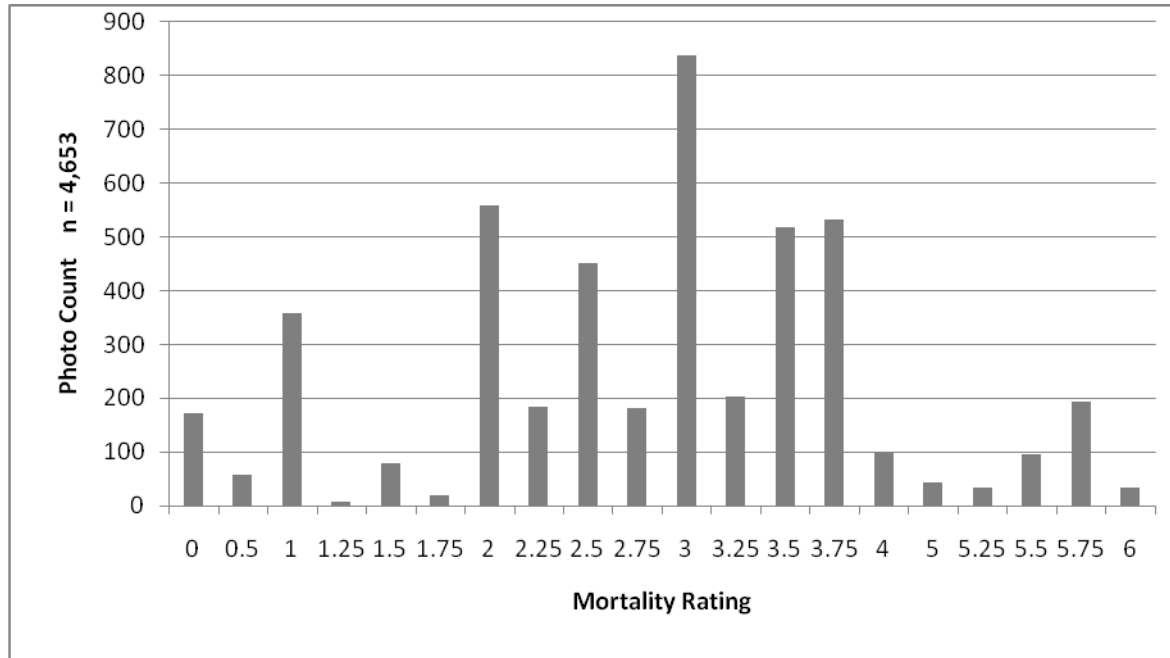


Figure 6. Look-at point frequency distribution.

By lumping fractional mortality ratings into groups that represent levels of mortality (i.e., 0-.75—no unusual mortality; 1 -1.75—low mortality; 2-2.75—medium mortality; 3-4—high mortality; and 5-6—residual forest), patterns of mortality become more obvious (Figure 8 and Figure 9).

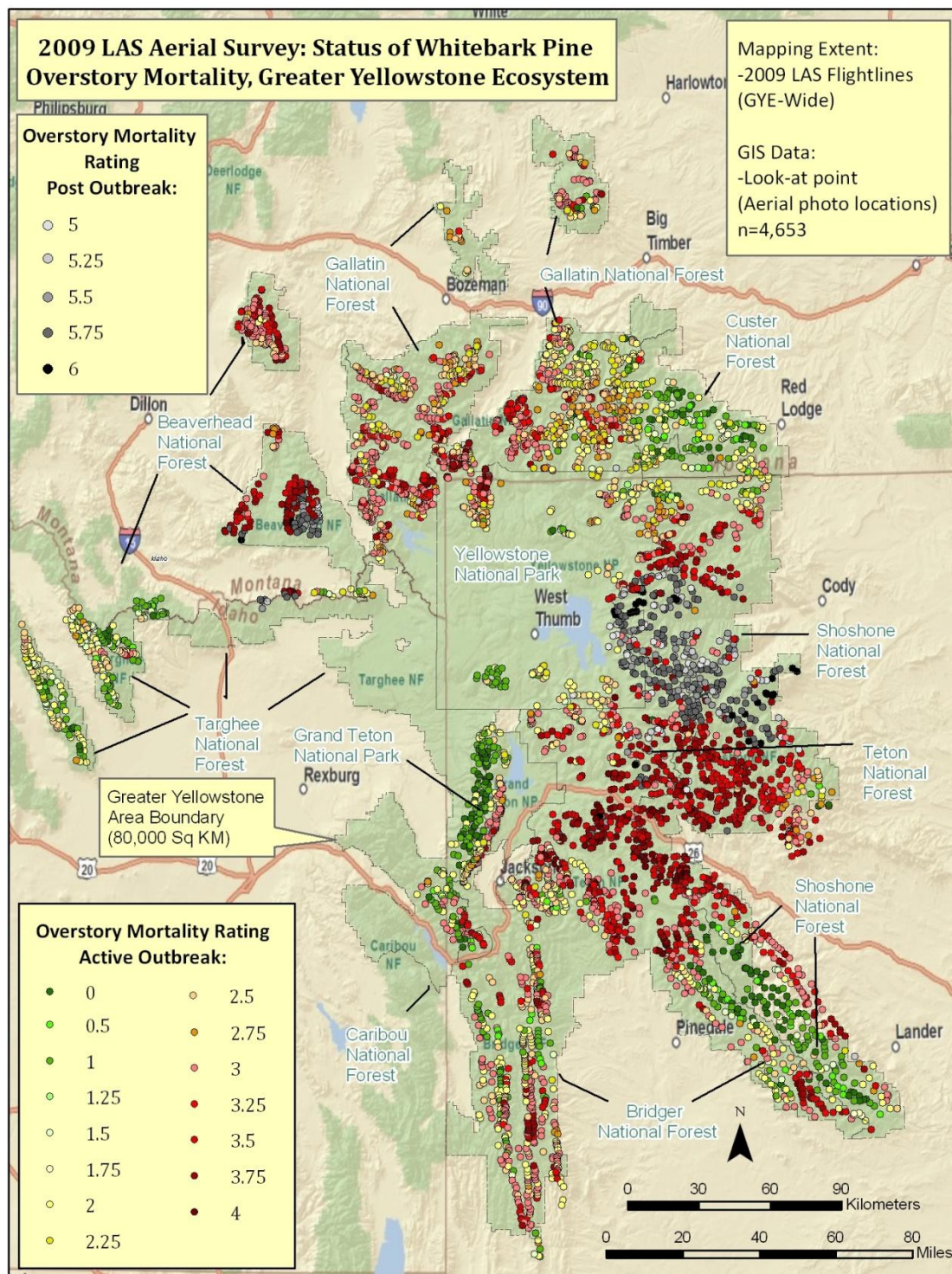


Figure 7. Look-at point mortality map.

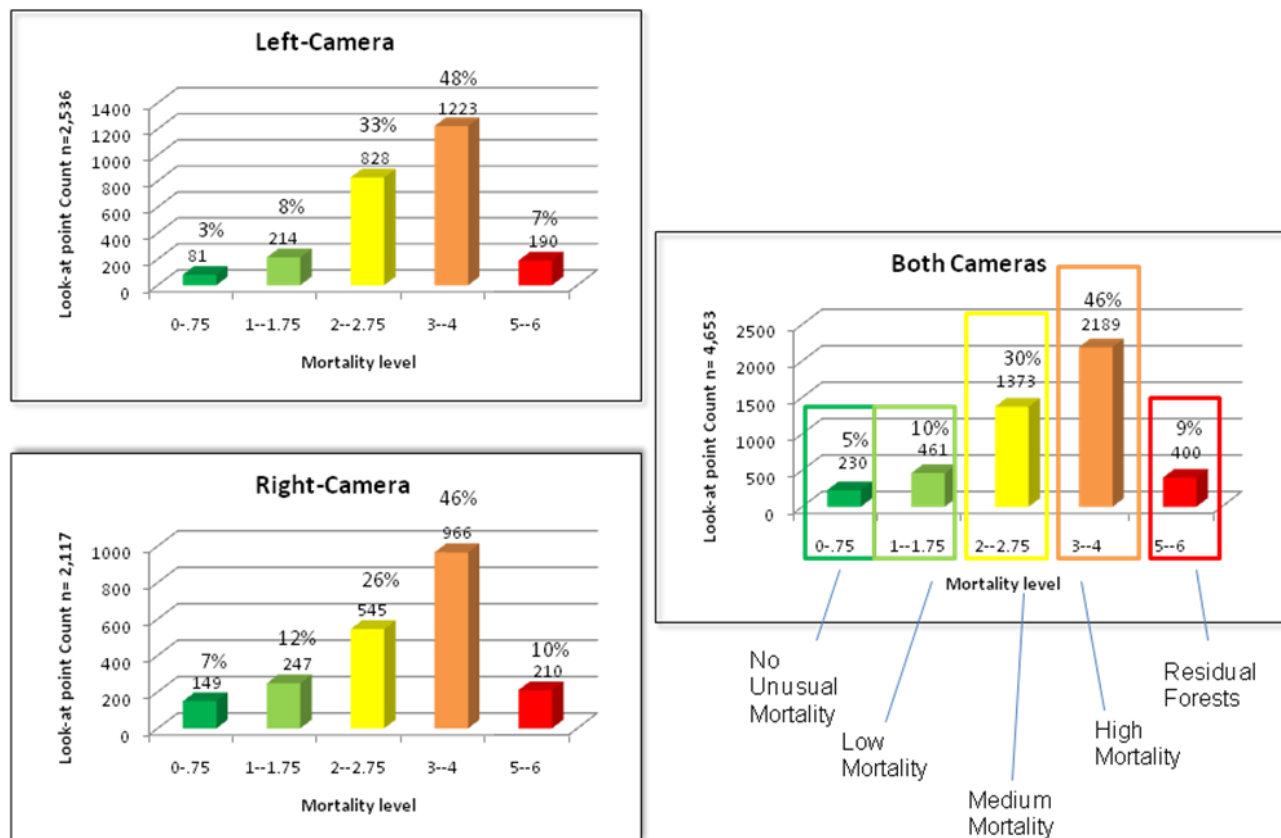


Figure 8. Mortality level frequency distribution of aerial photos (look-at points).

Over one half (55%) of the photos were classified with a high mortality or residual forest rating (3-6), indicating coalesced beetle outbreaks and widespread whitebark pine mortality. 30% of the photos were classified with a medium level of mountain pine beetle-caused mortality (2-2.75). 10% of the photos were classified with low levels of mountain pine beetle-caused mortality (1-1.75). And 5% of the photos showed no unusual mountain pine beetle-caused mortality (0-0.75).

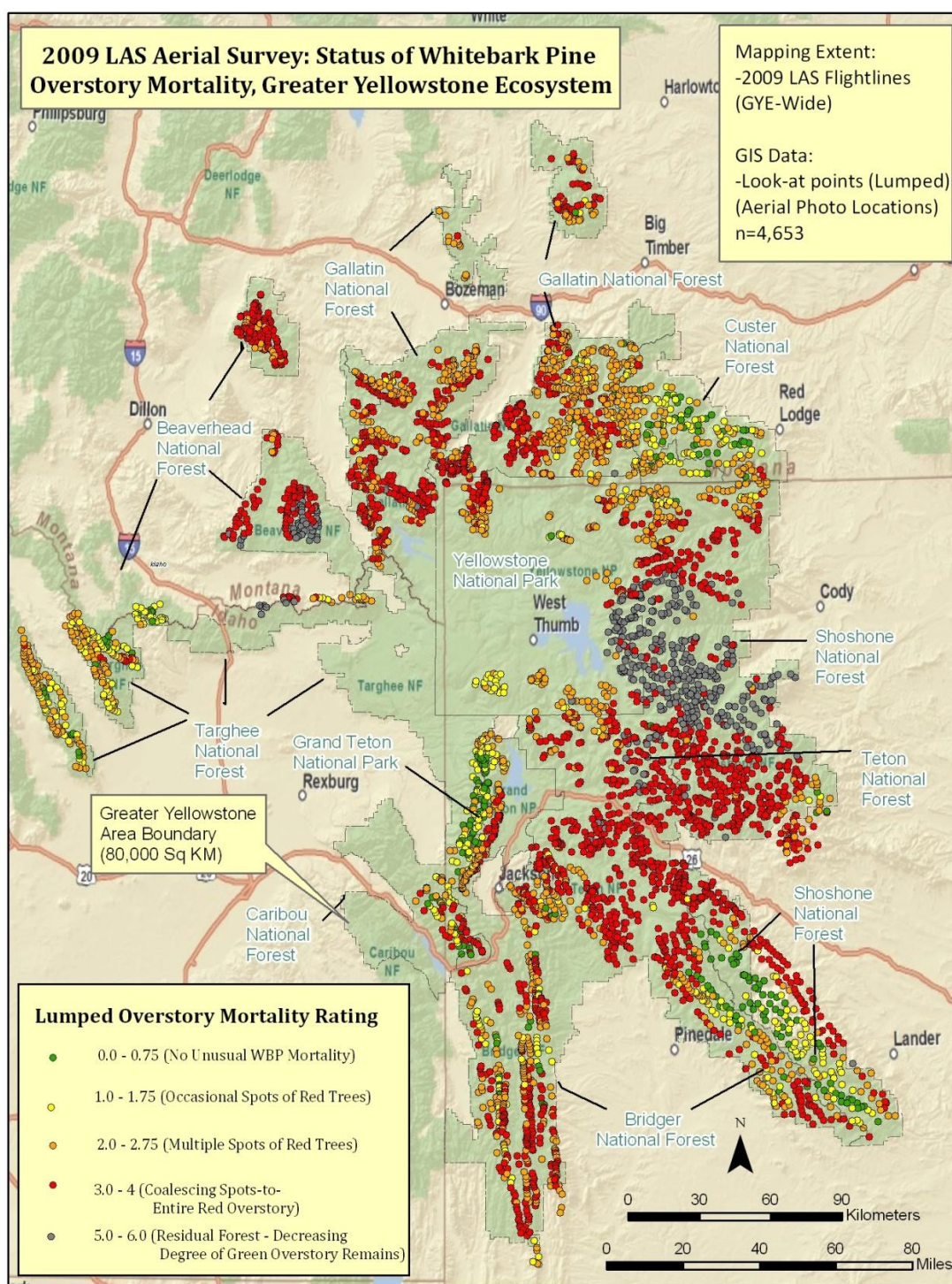


Figure 9. Look-at point lumped mortality level map.

Sampled sub-watershed mapping. The 4,653 look-at points captured mortality information for 2,528 sub-watersheds. Of these sampled sub-watersheds, 51% were categorized with a high mortality ranking (3-6), indicating heavy mortality in the form of coalesced beetle outbreaks, 31% received a medium ranking (2-2.9), 12% received a low ranking (1-1.9) and 6% had no unusual mountain pine beetle-caused mortality (0-.9) (Figure 10).

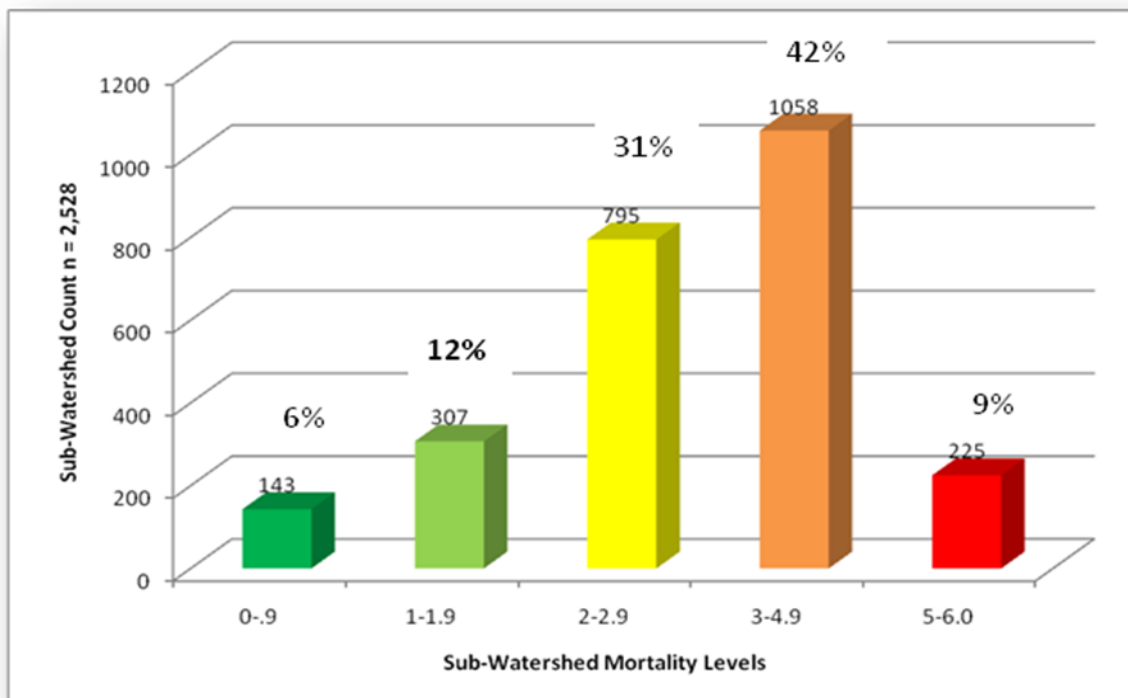


Figure 10. Mortality level frequency distribution of sub-watersheds.

Figure 11 is a map showing mortality level ratings for the sampled sub-watersheds. This map does not delineate the whitebark pine distribution within the sub-watershed. By plotting the mortality level of the sub-watersheds onto a map, widespread decline of GYE whitebark pine is revealed, and mortality patterns related to landscape characteristics become apparent.

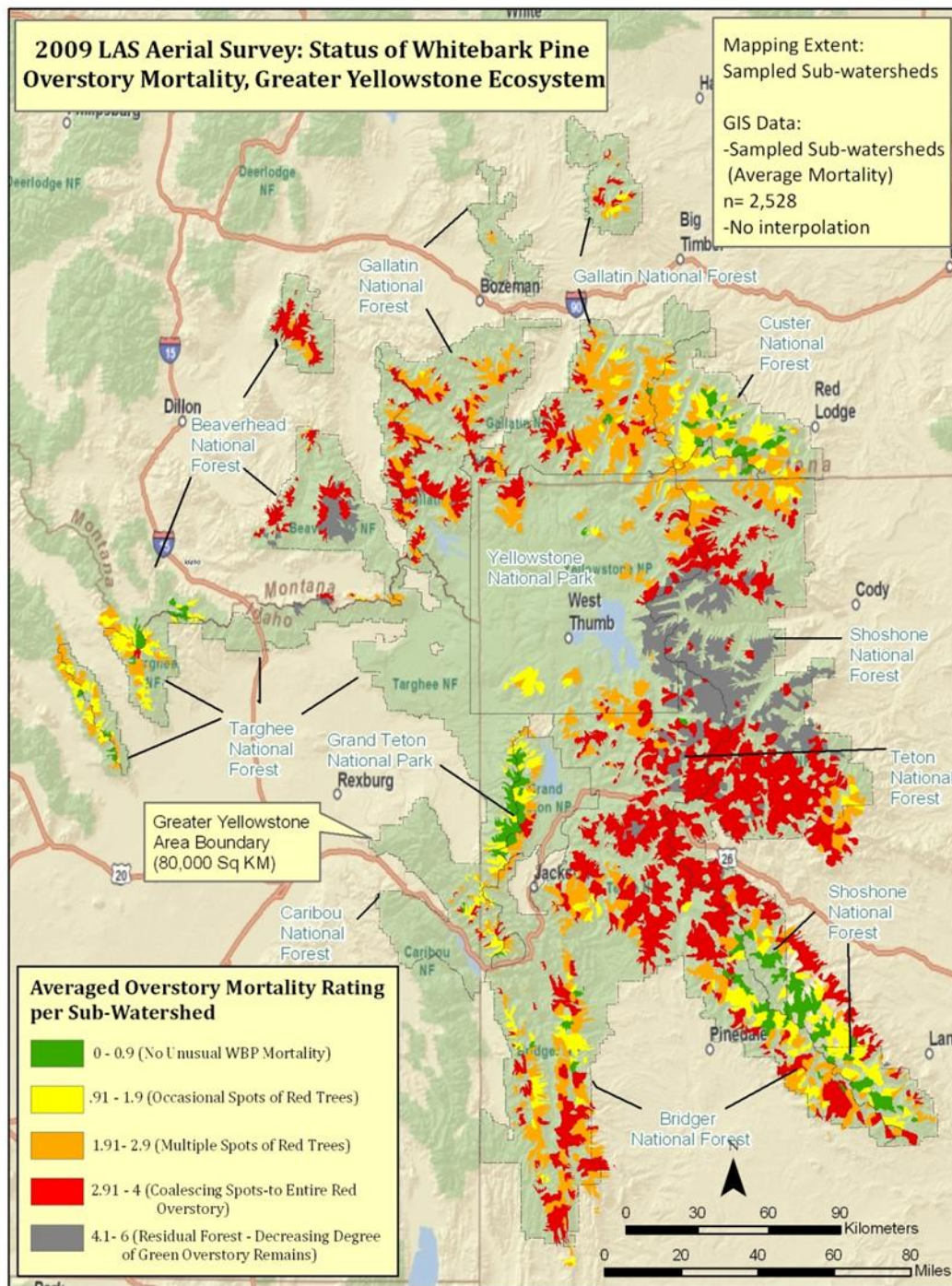


Figure 11. Sub-watershed mortality map.

Interpolated surface mapping. We sampled 2,528 of 4,436 GYE whitebark pine sub-watersheds (57% of sub-watersheds or 73% of the total area of the sub-watersheds). The mortality values of the remaining sub-watersheds (42% by count or 27% of the sub-watershed area) were estimated using an interpolated surface. The surface was generated using kriging. Kriging is a geostatistical method that involves autocorrelation (the statistical relationship among the measured points). Because of autocorrelation, not only does kriging produce a prediction surface, but it also provides a measure of the accuracy of the predictions. Kriging is most appropriate when you know that there is a high level of autocorrelation. We used two indices of spatial autocorrelation, Moran's I and Ripley's K functions to determine the data level of autocorrelation (Figure 12).

Moran's I

$$I = \frac{N \sum_i \sum_j W_{i,j} (X_i - \bar{X})(X_j - \bar{X})}{(\sum_i \sum_j W_{i,j}) \sum_i (X_i - \bar{X})^2}$$

Where N is the number of cases

X_i is the variable value at a particular location

X_j is the variable value at another location

\bar{X} is the mean of the variable

W_{ij} is a weight applied to the comparison between location i and location j

Ripley's K

$$L(d) = \sqrt{\frac{A \sum_{i=1}^N \sum_{j=1, j \neq i}^N k(i,j)}{\pi N(N-1)}}$$

Where A is area, N is the number of points, d is the distance $k(i, j)$ is the weight, which (if there is no edge correction) is 1 when the distance between i and j is less than or equal to d and 0 when the distance between i and j is greater than d . When edge correction is applied, the weight of $k(i,j)$ is modified slightly.

Figure 12. Moran's I and Ripley's K function equations.

Both Moran's I and Ripley's K function indicate that the 2009 LAS look-at points have a strong positive spatial autocorrelation and therefore are appropriate for kriging to interpolate mortality values in non-sampled areas (Figure 13).

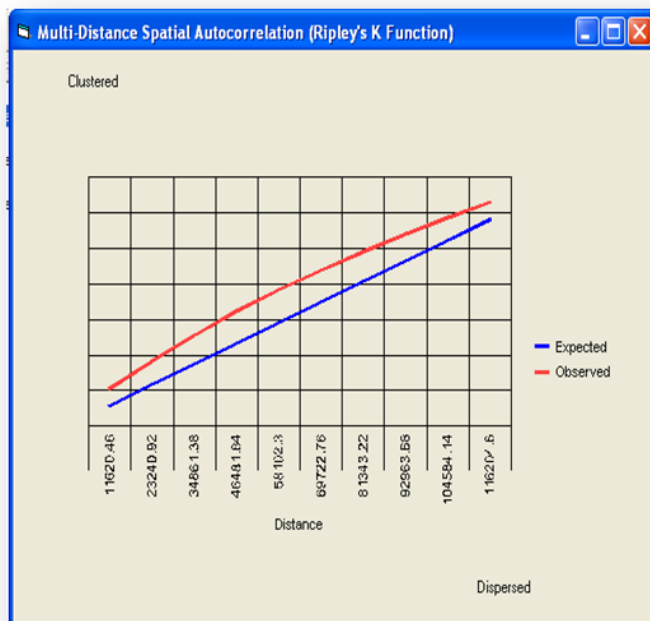
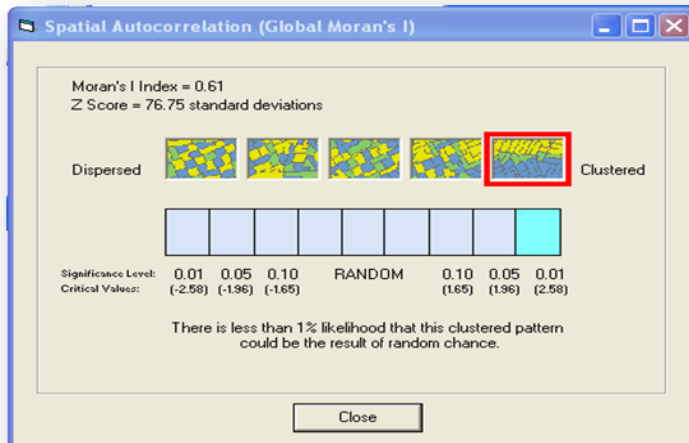


Figure 13. Results of Moran's I and Ripley's K Function.

The output variant raster provides a measure of the accuracy of the predicted mortality surface (Figure 14). The map displays the kriging variance at each output raster cell. There is a 95.5 percent probability that the actual mortality-value at the cell is the predicted raster value, plus or minus two times the square root of the value in the output variant raster. Applying the above information the 2009 LAS output variance raster indicates accuracy values of between \pm or $-$.25 to 1 mortality rating depending on the distance from the sampled sub-watersheds.

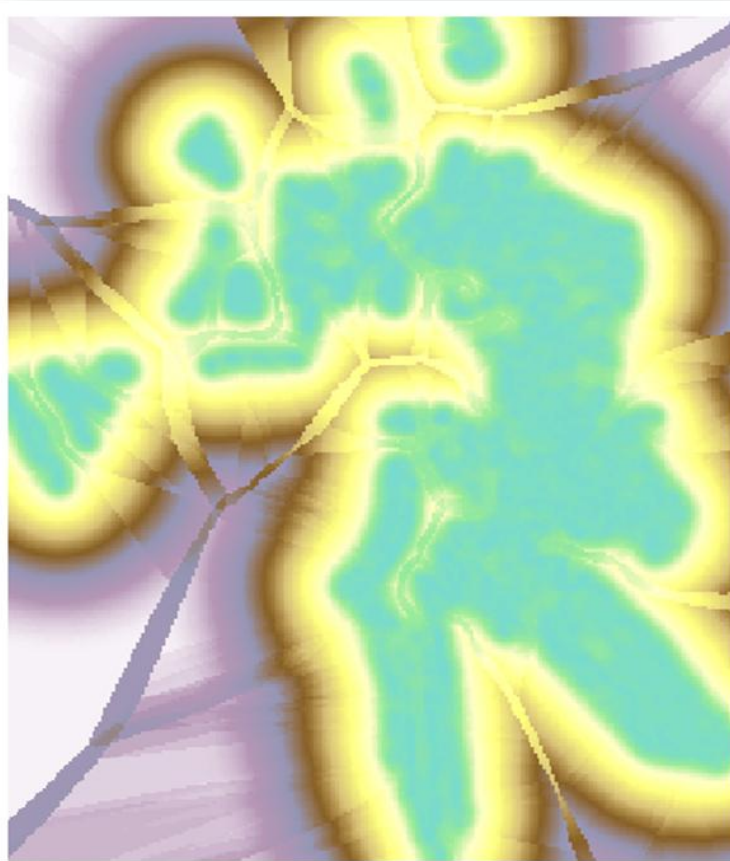


Figure 14. The 2009 LAS output variant raster based on look-at points.

GYWPC Whitebark Pine Distribution Level Mapping. The sampled sub-watershed mortality data and the interpolated mortality surface were clipped by the GYWPC Whitebark Pine Distribution layer in order to isolate areas of whitebark pine within each sub-watershed.

The resulting layer is the whitebark pine distribution mortality layer, which is a combination of both sampled and interpolated mortality values. This layer indicates that 39% of whitebark pine area in the GYE showed high levels of mortality (3-4.9), 36% of the whitebark pine area showed medium levels (2-2.9), 13% showed low levels (1), 7% were classified as residual forests (5-6) and 5% showed an unaffected condition (0) (Figure 15). Figure 16 is a map showing the GYWPC Whitebark Pine Distribution by average sub-watershed mortality rankings. Note: The sub-watershed remains the minimum mapping unit and therefore each of the resulting polygons generated per sub-watershed have the same mortality rating. It is important to note that clipping to the polygons of the GYCC WBP Distribution does not enable the data to be used for stand-level mortality calculations.

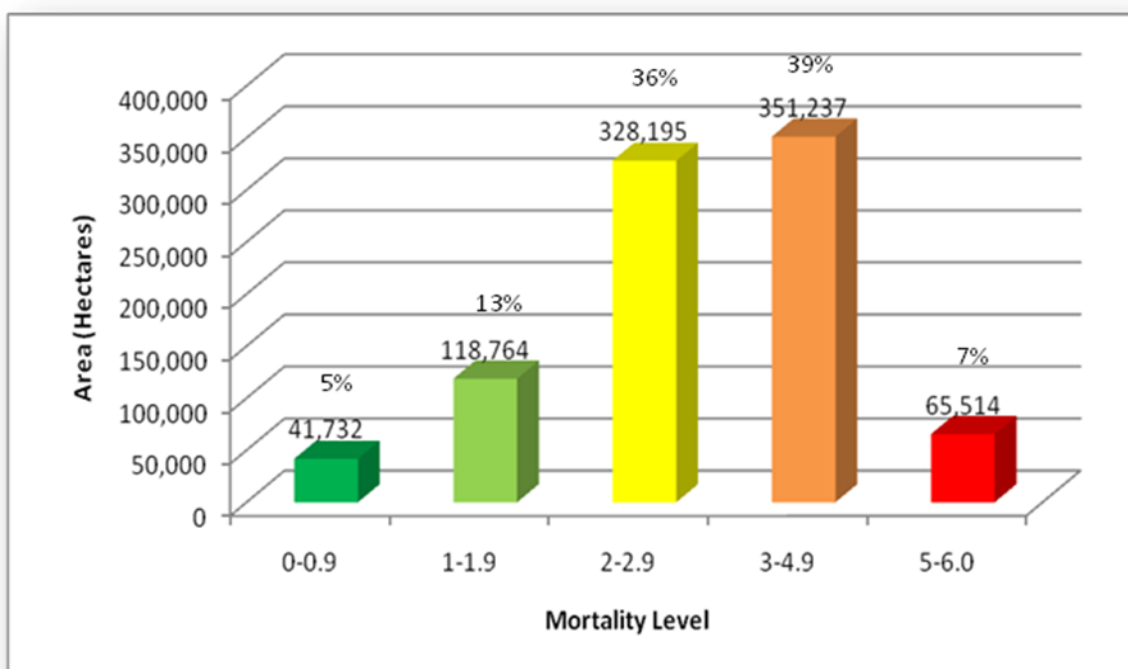


Figure 15. Estimated whitebark pine area by mortality level.

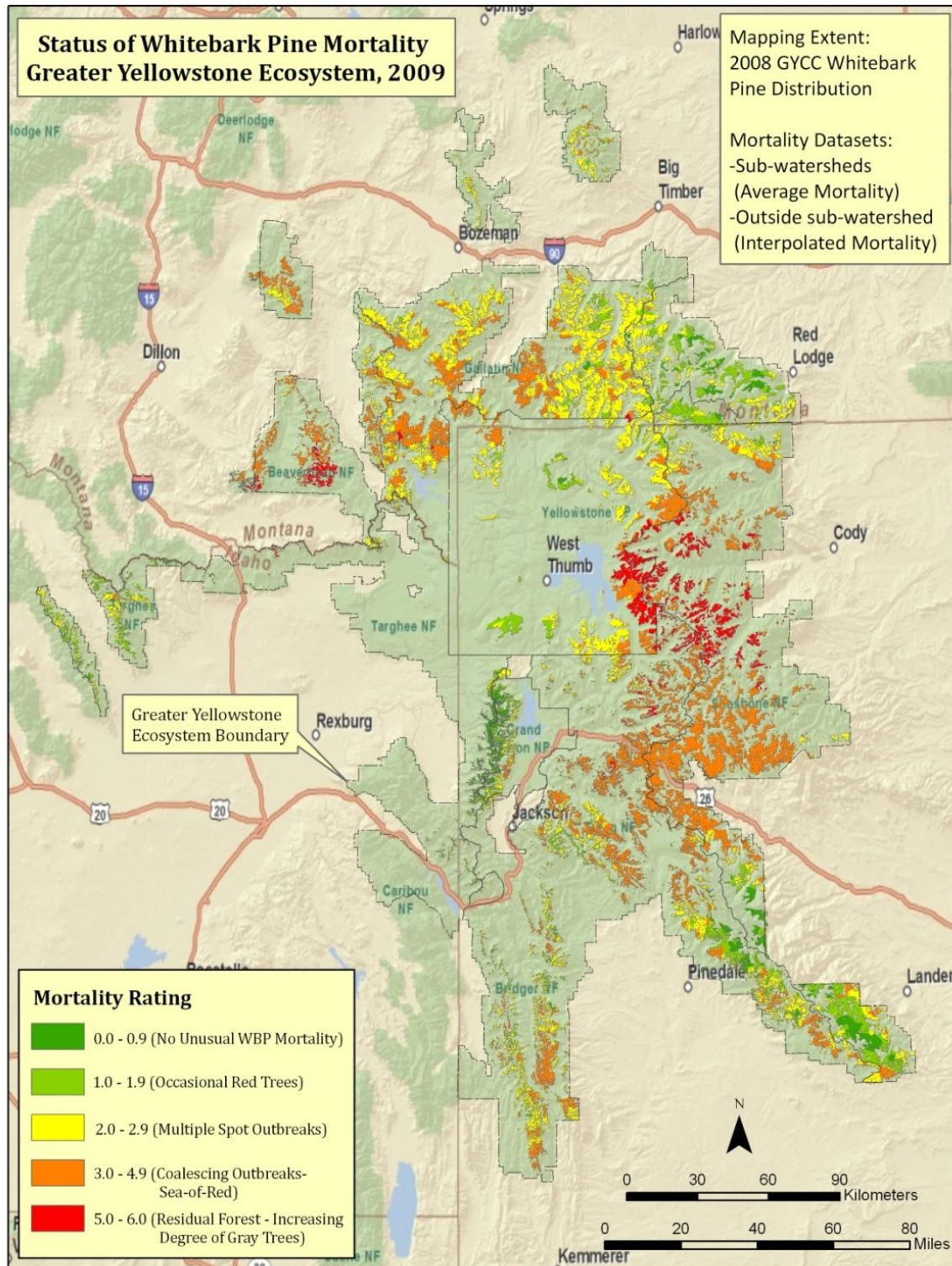


Figure 16. GYWPC whitebark pine distribution mortality map.

Mortality by GYE administrative units

This study reveals that whitebark pine mortality levels are distinctly related to geographic location and associated landscape characteristics. The whitebark pine forests of the Beaverhead-Deerlodge and Shoshone National Forests showed high mortality levels. The Bridger-Teton also showed high mortality except in portions of the Wind River Range. The whitebark pine forests of Gallatin National Forest showed medium to high levels. The Custer and Caribou-Targhee National Forests and Yellowstone and Grand Teton National Parks showed relatively low mortality levels (Figure 17).

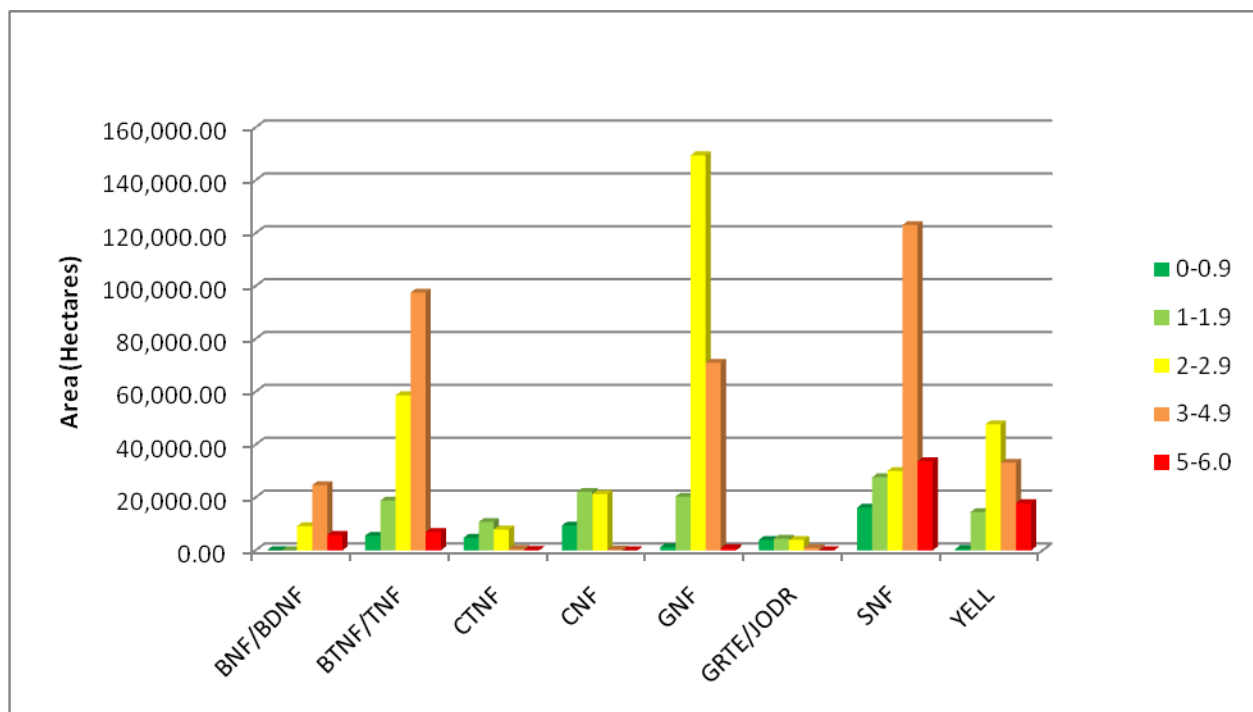


Figure 17. Mortality rating by administration units (0-0.9—no unusual mortality; 1-1.9—low mortality; 2-2.9—medium mortality; 3-4—high mortality, and 5-6—residual forest after a major outbreak).

The following series of maps, one for each major administrative unit, shows in more detail the spatial pattern of mortality across the GYE (Figures 18, 19, 20, 21, 22, 23, 24 and 25).

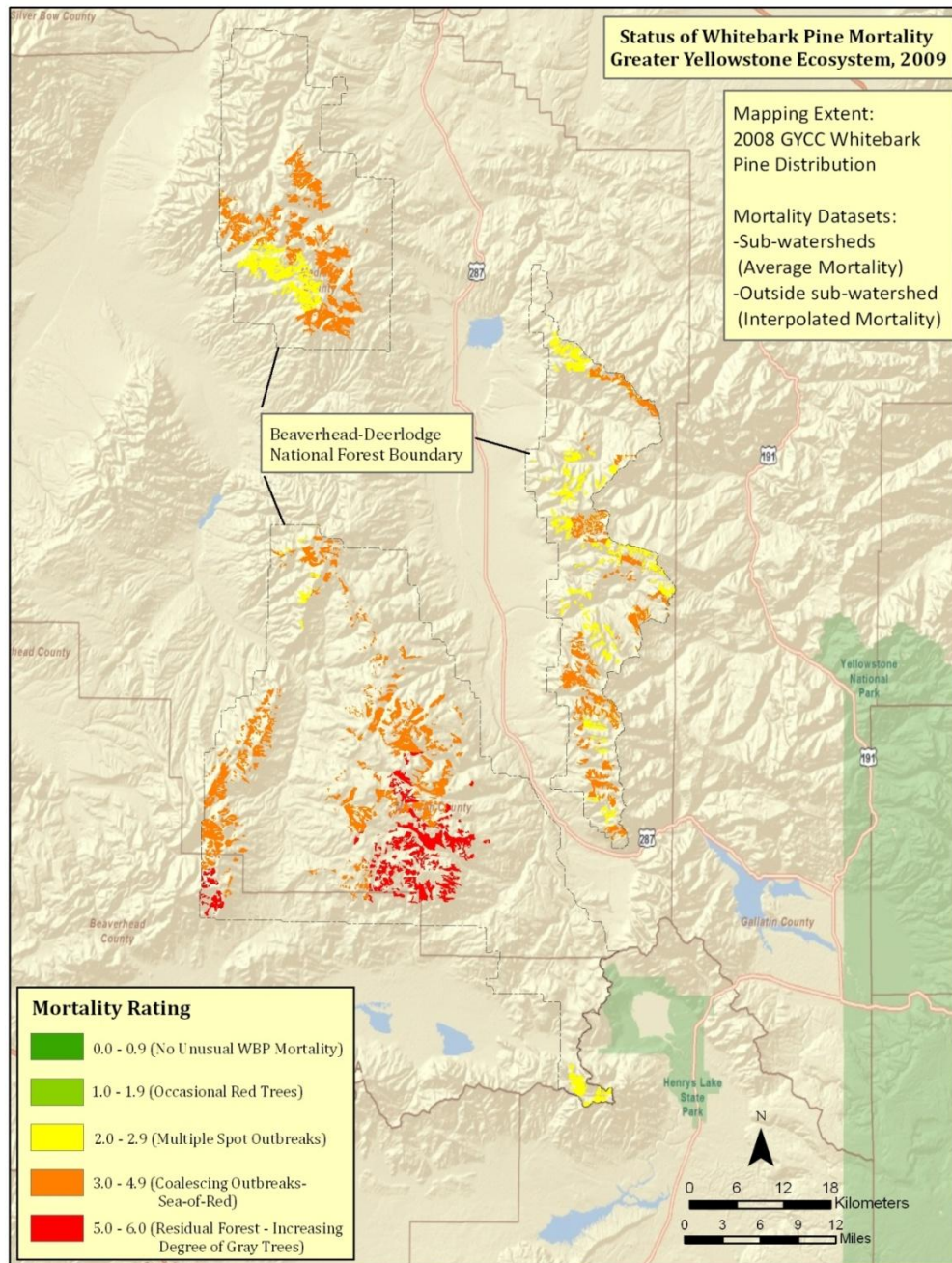


Figure 18. Beaverhead-Deerlodge National Forest (NF) GYWPC whitebark pine distribution mortality map.

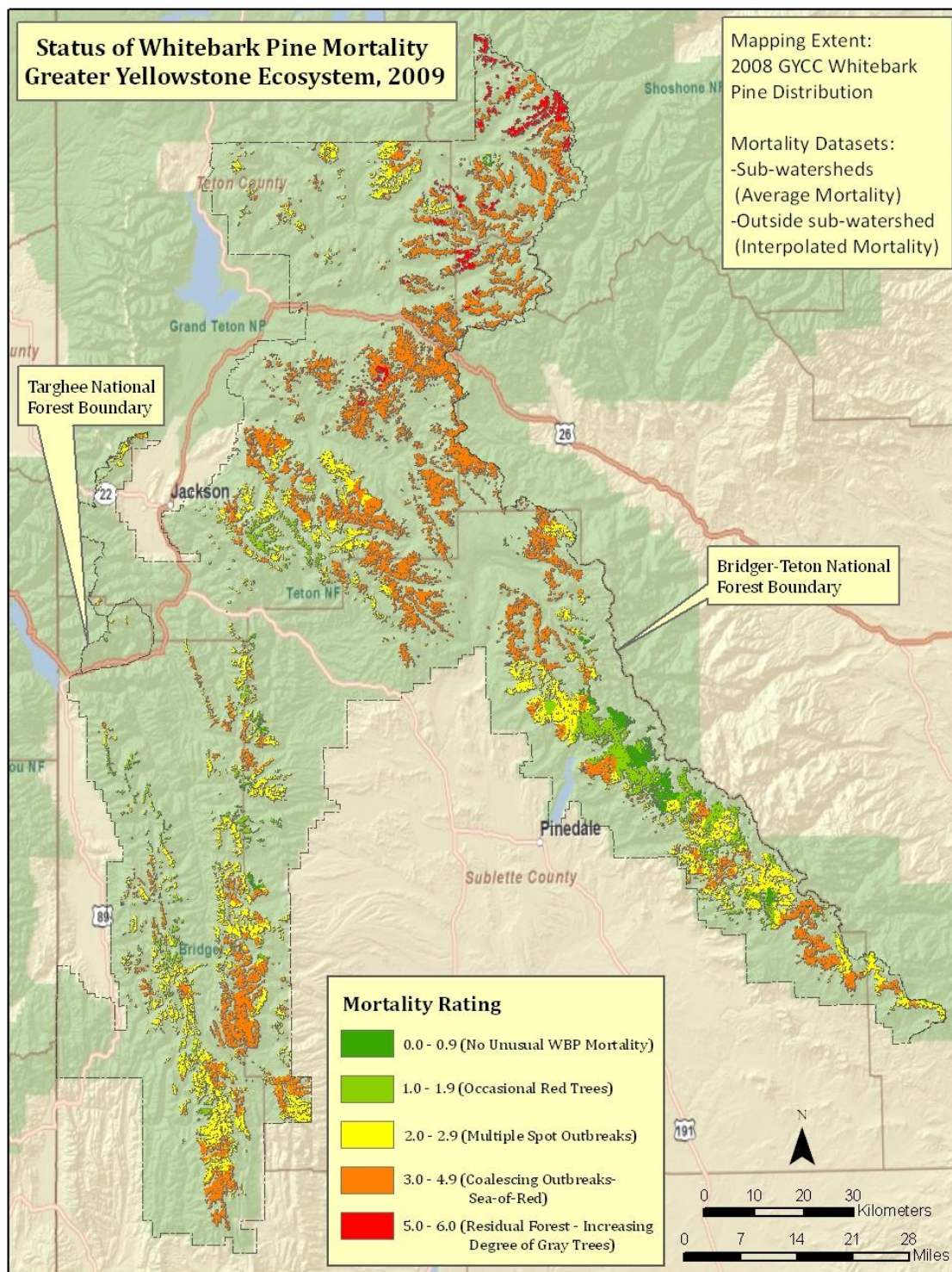


Figure 19. Bridger-Teton NF GYWPC whitebark pine distribution mortality map.



Figure 20. Caribou-Targhee NF GYWPC whitebark pine distribution mortality map.

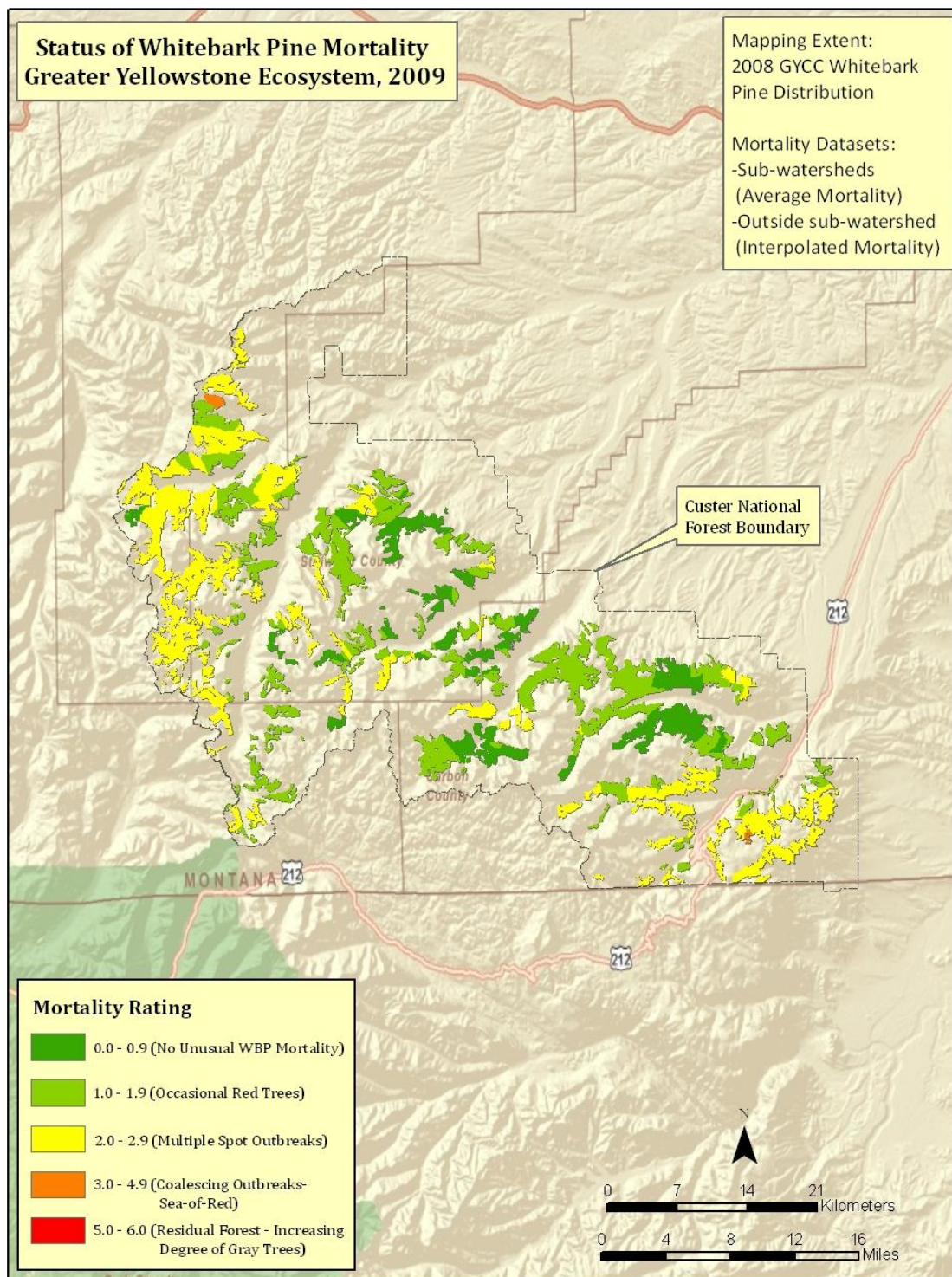


Figure 21. Custer NF GYWPC whitebark pine distribution mortality map.

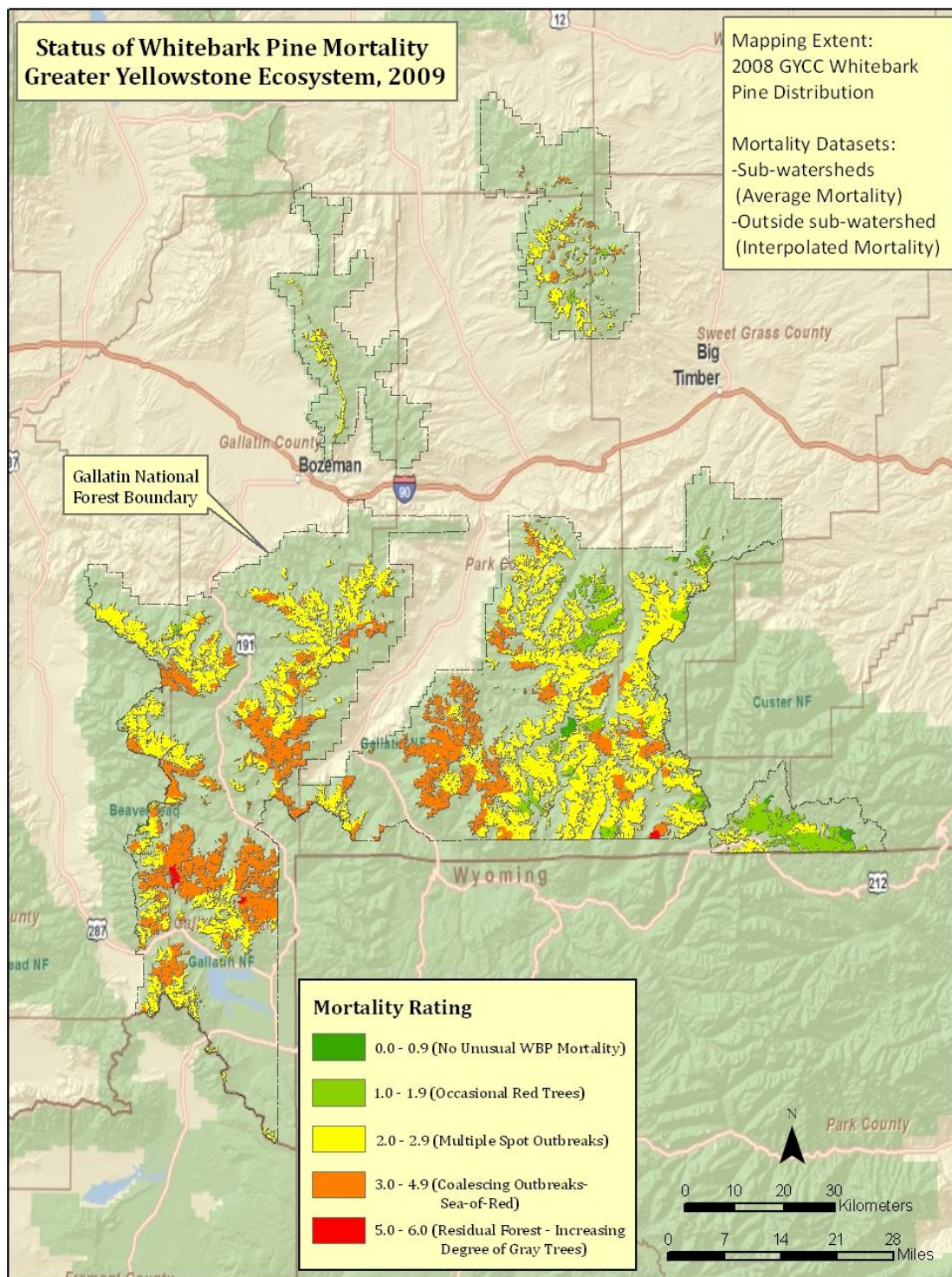


Figure 22. Gallatin NF GYWPC whitebark pine distribution mortality map.

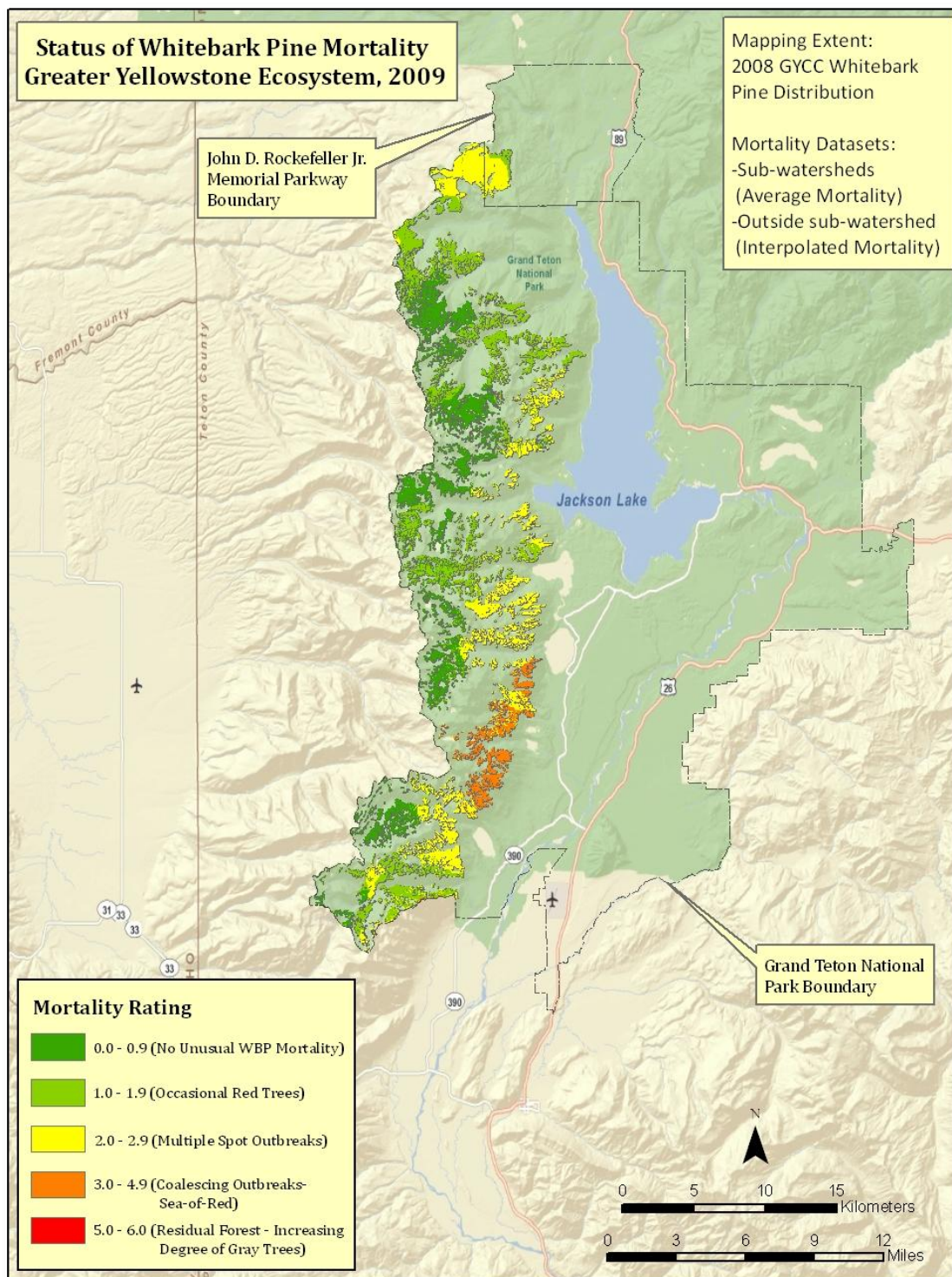


Figure 23. Grand Teton National Park GYWPC whitebark pine distribution mortality map.

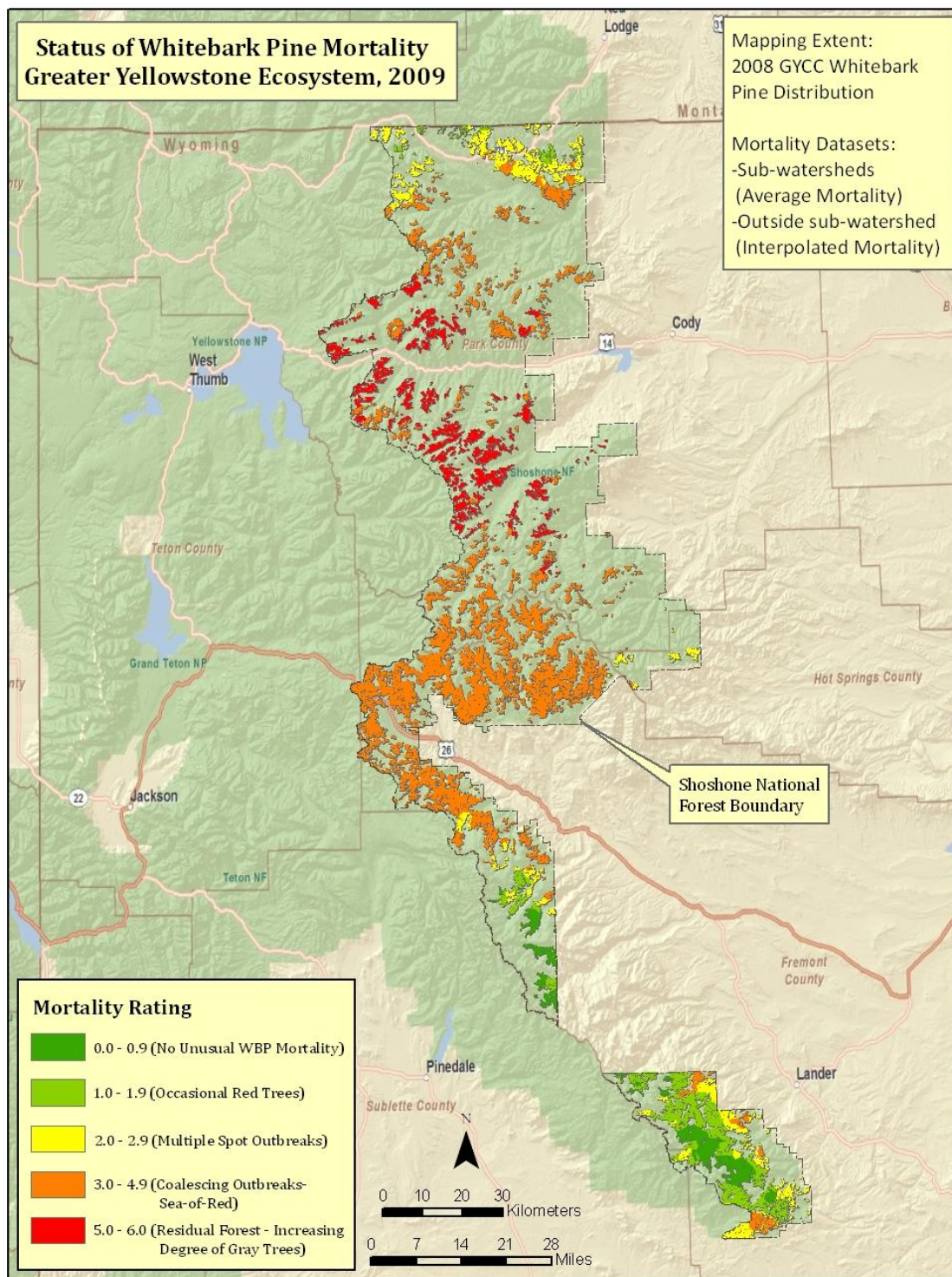


Figure 24. Shoshone NF GYWPC whitebark pine distribution mortality map.

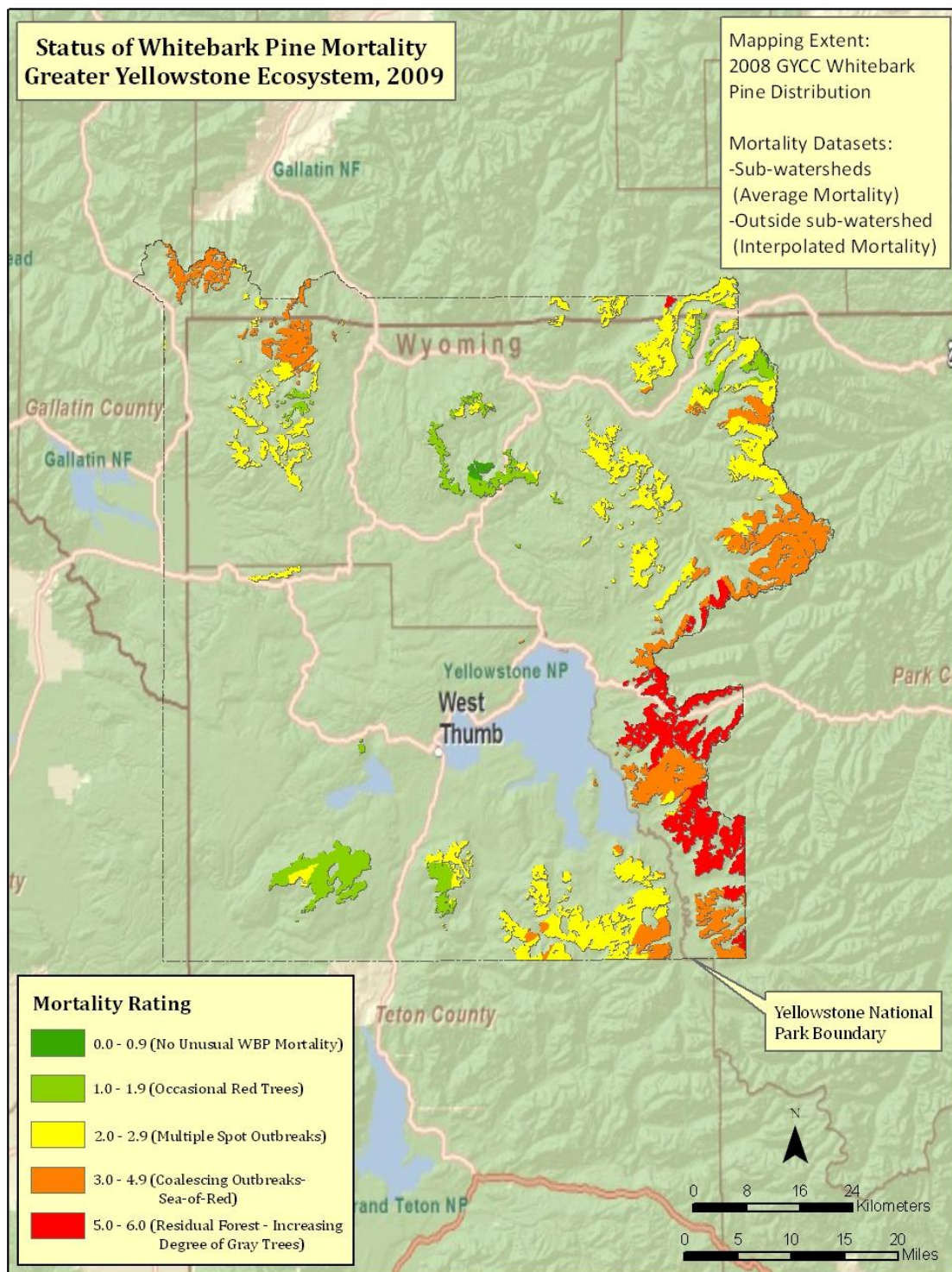


Figure 25. Yellowstone National Park GYWPC whitebark pine distribution mortality map.

Landscape-level ground verification

The selected viewpoints provided a vantage point that adequately simulated the perspective that the overflights provided and allowed us to effectively compare what was photographed and classified to what was seen and classified on the ground. The viewpoints allowed for the verification of a total of 238 or about 10% of the sub-watersheds that were sampled with look-at points (Figure 26). The ranking from the original classification of the aerial photography was compared to the mortality ranking assigned on the ground. Results indicate that the two methods produced very similar mortality ratings. If the rankings were different, it was .25 to .5 of a category. In approximately 5% of the cases, there was a large difference of .75 to as much as 1 full category difference. Most of the large differences can be explained by observation variability (see discussion section). Categories 0, 1 and 2 had the majority of the large differences, and categories 3 and above had the minority of large differences between the ground observations and the aerial photos. We found that there was a tendency to underestimate whitebark pine mortality in mixed conifer forests in the aerial photography compared to the ground observations. This is best explained by the tendency to consistently underestimate the whitebark pine component in mixed forests when viewed using aerial photography. Conversely, in pure whitebark pine stands, it was more often the case that mortality was overestimated when viewed using aerial photography compared to the ground observations. This may best be explained by the tendency while viewing the photography to focus on “looking for red trees,” resulting in increased observer sensitivity to mortality. Despite

these tendencies, we conclude that there is a strong correlation between how mortality was recoded and perceived in the photos and how mortality was perceived on the landscape.

Importantly, landscape-level verification validated the need for use of remote sensing in order to effectively provide a comprehensive, qualitative assessment of whitebark condition. In the field it was difficult and time consuming to view even 10% of the area that was assessed from the air. Also, the viewpoints obtained from the overflights greatly enhanced our ability to view and quantify landscape-level, beetle-caused mortality. The aerial perspective provided an unobstructed view of the forest overstory and shortened the time spent gathering data and assessing a large landscape.

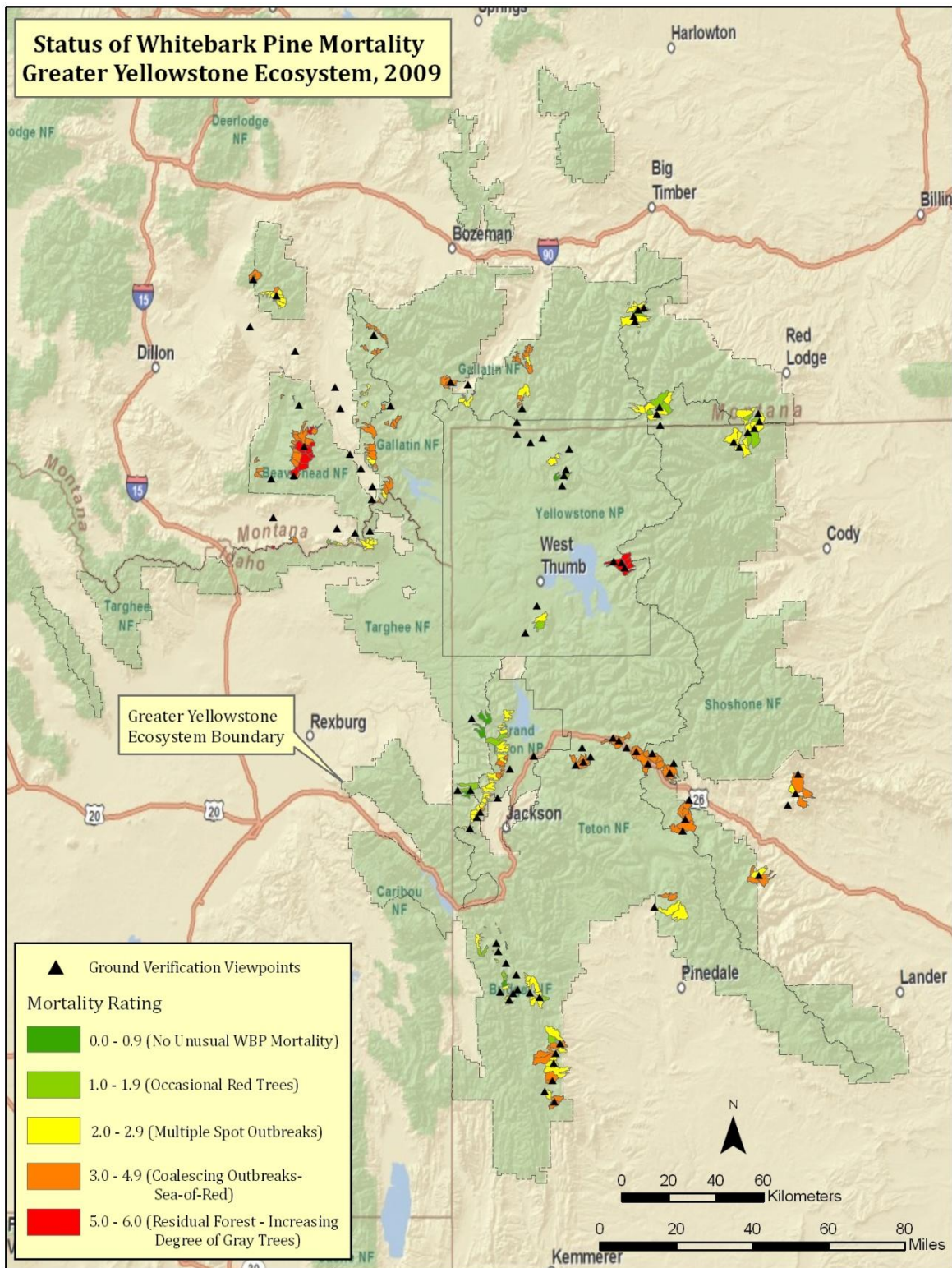


Figure 26. Ground verification viewpoints and associated sub-watersheds.

Stand-level observations

The stand-level observations allowed us to evaluate critical ecological factors that cannot be measured through remote sensing. The road-side stands we selected provided us with an on-the-ground perspective that allowed us to effectively measure individual tree and stand characteristics in both active outbreaks and residual forests (Table 1). We examined and recorded qualitative information for a total of 17 stands along the road transects or within close walking distance. We collected information regarding the intensity of current beetle attacks by examining attack densities. We also examined beetle galleries to determine beetle success in new and old attacks, brood productivity, and resistance and defensive responses within specific trees. We assessed recruitment in all cohorts. The stands were widely distributed across the GYE and revealed the variability in the intensity and prevalence of 2009 mountain pine beetle attacks. We noted very high levels of brood production in the southern regions and retarded development in all phases of development (larvae, pupae, and tenoral adults) in the northern ranges of the GYE. Likewise, we observed very different levels of cone crops between the southern regions, where cones were plentiful, and the northern regions where far fewer cones were seen. This observation is not unusual within the distribution of whitebark pine, as cone production varies across the ecosystem. Assessing mortality on the ground level showed the current-year attacks more easily, while assessing mortality using the aerial approach more readily identifies the previous year's attack. In several areas of high mortality, many of the trees that showed signs of current attack when viewed at ground level still appeared green from the air.

National Forest	Location	Current Attack	Recruitment	Cone Crop	Brood Production	WPBR	MPBM rating
Bridger-Teton	Pinnacle Buttes (Bonneville Pass)	extreme	moderate	high	high	Low	3.75
Bridger-Teton	Salt River Range	high	low	extreme	n/a	Low	2.5
Bridger-Teton	Wyoming Range	extreme	low	extreme	n/a	Low	3.5
Bridger-Teton	Mount Leidy	extreme	moderate	moderate	n/a	Low	3.75
Bridger-Teton	Union Pass	extreme	low	high	n/a	moderate	3.75
Shoshone	Crow Canyon (Crowheart, Wyoming)	moderate	moderate	high	n/a	n/a	3.5
Gallatin	Irma Mine Road (Republic Creek)	moderate	n/a	n/a	n/a	n/a	2.25
Gallatin	Eagle Creek Road (Jardine, Montana)	high	low	low	low	moderate	3.5
Gallatin	Packsaddle Peak	extreme	low	moderate	high	n/a	3.5
Gallatin	Lulu/Daisy Rd (New World Mine)	low	high	high	low	n/a	2.75
Custer	Beartooth Hwy (US Hwy. 212)	low	high	low	low	n/a	2.5
Custer	Picket Pin Rd	moderate	high	low	low	moderate	2
Beaverhead	Mill Creek (Tobacco Root Range)	low	high	moderate	low	moderate	3
Beaverhead	Wisconsin Creek (Tobacco Root Range)	extreme	low	low	moderate	Low	3.25
Beaverhead	Gravelly Mountain Road	low	low	high	low	extreme	3.5/5.5
Caribou-Targhee	Baldy Knoll	moderate	low	high	high	Low	1
Caribou-Targhee	Pinocle Road	low	moderate	high	low	high	1.5

Table 1. Stand-level ground verification observations.

Discussion

Discrepancies between GYWPC distribution and LAS look-at point layers

A basic assessment of spatial accuracy of the GYWPC Whitebark Pine Distribution layer was conducted during this project. We performed this assessment because this layer was used as our project area boundary and was the base layer for all area calculations. To assess the spatial accuracy of this layer, we examined random polygons in Google Earth and compared them with both the base imagery and the LAS aerial photos. Overall we found this spatial layer to be relatively accurate in identifying the presence or absence of whitebark pine. However, as with any vegetation GIS layer, this layer it is not 100% accurate. We identified non-systematic spatial errors (i.e., errors not associated with systematic spatial shifts due to map projection errors or the like). We found errors of commission in which GYWPC polygons were displayed in areas where the both the background imagery and LAS photo did not show forest stands. We also identified errors of omission; specifically LAS photos showed stands of whitebark pine but the GYWPC layer did not have a polygon in the area.

It is beyond the scope of this project to even speculate as to why these apparent errors are being manifest, let alone perform a full-blown accuracy assessment or attempt to fix these errors. Nevertheless, because these distribution discrepancies have such a significant impact on the results of this study, we suggest that the data derived from this study be used to address and potentially help correct mapping errors in the GYWPC Whitebark Pine Distribution layer.

Areas showing resistance to beetle outbreaks

The 2009 LAS project identified areas within the current distribution of whitebark pine that are more resistant to climate change than others. One such area is the central core of the Wind River Range. The Wind River Range's resistance to climate may be due to being the highest mountains in the GYE and more than even Glacier National Park (GNP), the Wind Rivers constitute the most complex glacial system in the contiguous U.S. Rocky Mountains. The moderating influence of high mountains, permanent snow and ice result in a local climate that currently remains too harsh to support outbreak populations of mountain pine beetles. Unfortunately, glaciers in the Wind Rivers, like in GNP, are shrinking at an alarming rate (Pochop et al. 1990). Once the permanent snow and ice is lost, we expect a threshold event that will dramatically improve thermal habitat for mountain pine beetle in this area.

Another area that was identified as resistant to climate change is the Beartooth Plateau. It is perhaps more promising than the Wind River Range. The Beartooth Plateau is the largest contiguous area above 3,000 m in the U.S. Rocky Mountains. This large, high plateau is extremely cold, particularly in winter. The combination of high elevation and cold temperature has resulted in a vast expanse of dwarf/Krummholz whitebark pine forests. These forests do not provide many trees large enough for the beetle to make a living; therefore, it is unsusceptible to attack for the foreseeable future. Nevertheless, even these small trees are susceptible to white pine blister rust. In areas of high infestation, these forests may be impacted by this introduced species in the future.

These locations could provide areas of refuge for whitebark pine for intermediate time scales, based on current climate projections. Likewise, because the Krummholtz growth form is too small for beetles to attack and are capable of assuming an upright growth form under more moderate climate conditions, in many circumstances these areas may be key to the long-term survival of the species.

Limitations of the LAS Method

Observer variability. Manually classifying beetle-caused mortality is inherently subjective in nature, and is therefore susceptible to observation variability. Examining a landscape or a photograph of a landscape and manually assigning a numeric rating for tree mortality is influenced by an observer's experience and skill level. As a result, individual observers perceive and interpret the amount and intensity of beetle-caused mortality differently, which results in observers assigning different mortality ratings to the same landscape conditions. Because of observer variability associated with this method, there are accuracy limitations which reduce accuracy levels compared with more objective remote sensing approaches. Efforts were made throughout the project to identify observer variability and determine how to limit its influence on assigned mortality values across the landscape. When we isolated the observation variability by having different observers categorize mortality on the same landscape, we found that the range of variability was generally between .25 to .5 with the rare occurrence of 1 or more. We found that the largest variability occurred in the 0, 1 and 2 categories because these lower categories seem to have more ambiguity and result in greater observer bias regarding mortality level. Conversely, in areas of categories 3 and above,

where the characteristics of coalescence are more obvious on the landscape, mortality classification tended to be more similar among observers.

In an effort to make the mortality maps more readable, we lumped our categories into bins that represent major types of mortality: 0-0.9—no unusual mortality; 1-1.9—occasional red trees; 2-2.9—multiple spot outbreaks; 3-4—coalescing outbreaks increasing to “sea of red”, and 5-6—residual forest after a major outbreak. By consolidating mortality into five units, we not only greatly reduced the negative effects of observer variability, but we also made the maps more readable.

In most cases the LAS method assigns one mortality rating per photo; therefore the method generalizes mortality across the area covered by the photo. This generalization is most severe in heterogeneous areas (i.e., areas containing various mortality levels within a small spatial area). We addressed this potential oversimplification of mortality in areas of complex mortality patterns by using Google Earth to add additional mortality rating points within the photo. Even with this modification, in some cases the resulting sub-watershed-level maps provide only a coarse representation of the true landscape condition. Thus, the resulting maps are better suited to identifying broad mortality trends over large geographic areas and are less well suited to providing detailed site-specific stand-level mortality information. Therefore, if someone is interested in the condition of an individual forest stand, we encourage that person to closely examine the area of interest within the photo and ground verify the area.

One of the important products resulting from this study is a set of mortality maps and associated spatial data at the sub-watershed level. Therefore, the minimum mapping unit (MMU) “the smallest size areal entity to be mapped as a discrete entity” (Lillesand and Kiefer 1994) is the sub-watershed level ranging in size from 150 to 3,000 ha for this study area. In many cases, this is a relatively large MMU; and research indicates that in general, the bigger the size of the MMU, the more the landscape diversity and heterogeneity is underestimated (Saura 2002). Thus, it is important to consider the fact that these maps likely generalize mortality conditions and that individual stand analysis will provide site-specific mortality data.

Independent assessment of computer models

The 2009 LAS of the GYE provided an independent assessment of previous computer simulations and indicated that mountain pine beetle outbreaks are outpacing computer simulations (Powell and Logan 2005, Logan and Powell 2009) that were based on climate warming projections. Specifically, the 2009 LAS project results indicated that outbreaks are spreading much faster than the models predicted and the consequences appear more severe than simulations indicated. The collapse beyond predicted levels was particularly evident in the Northern and Southern Wind River Range, Gros Ventre Wilderness and Teton Wilderness.

The discrepancy between predicted and actual findings may result largely from the fact that almost all our knowledge at the time of the model development was based on experience in lodgepole pine, and that whitebark pine is a vastly different ecosystem. As stated previously, mountain pine beetle was not historically considered to play a major role in the dynamics of whitebark pine because, under historical climate conditions, mountain pine beetle could not

flourish in the harsh environment of the high mountains. Therefore, the extent and intensity of the outbreaks that have already occurred in the whitebark pine systems were underestimated under these model assumptions.

Conclusion

This project effectively documented the current (2009) status of mountain beetle-caused mortality of whitebark pine across the GYE at the sub-watershed level. Because this project effectively mapped the geographic variability of whitebark pine mortality, we know the locations of forests that still remain as fully functioning ecosystems, with living, mature, cone-bearing trees, as well as the location and extent of forests with currently high, medium and low levels of mortality. This spatially explicit mortality information is intended to help forest managers develop and implement conservation strategies that include both preservation and restoration efforts. Specifically, the spatial data resulting from this project is intended to contribute directly to the Whitebark Pine Strategy presently being developed (to be completed by March 2010) by the GYWPC Whitebark Pine Subcommittee.

The information produced by this project, including geo-tagged photos, spatial data sets and mortality maps, provides a photographic and spatial data documentation of a widespread disturbance event resulting from unprecedented levels of mountain pine beetle outbreaks in whitebark pine forests of the GYE. The removal of whitebark pine overstory across large areas of the GYE is now well documented. However, the true impacts of the decline of this foundation and keystone species on ecosystem function are yet to be realized. We believe that this widespread high-intensity mortality may likely impact the ability of this species to provide

critical ecosystem services, and may threaten the very future of this ecosystem (Logan et al. 2010). One thing which seems inevitable is that this mortality event will remain an obvious landscape attribute for many decades to come.

Acknowledgments

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Appendix A: Mountain Pine Beetle-caused Mortality (MPBM) Rating System

J.A. Logan, W. W. Macfarlane and W.R. Kern

O (zero) – There is no unusual mountain pine beetle mortality on the landscape. “No unusual” refers to landscapes that may contain the occasional red tree but there is no evidence of mortality expanding to neighboring trees (Wind River Range 2006 and 2009).



W.W. Macfarlane

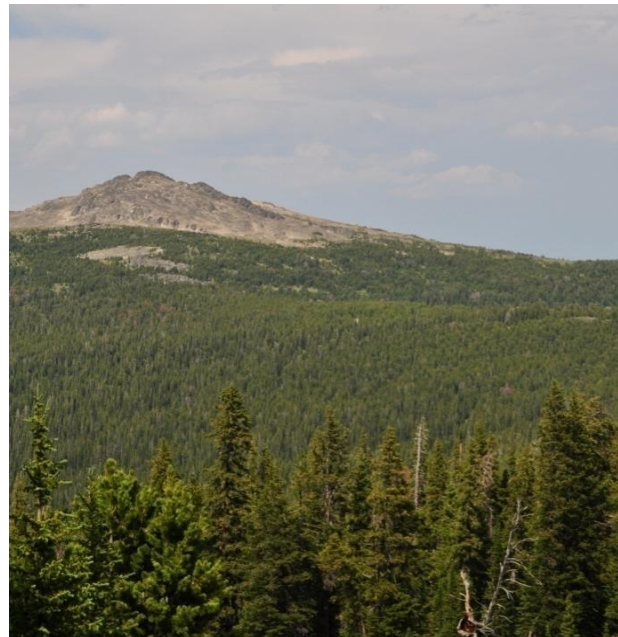


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1 (one) – There are occasional spots of red trees across the landscape but the spots do not show evidence of multi-year activity (Woody Ridge 2007; Picket Pin Mountain 2009).



J.A. Logan



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2-2.75 – There are multiple spots of red and gray trees across the landscape and spots show two or more years of subsequent mortality. This is a growing infestation that has a high probability of developing into a coalesced outbreak if weather conditions remain favorable. The increasing magnitude of these spots is assessed with a **2.25**, **2.5** and **2.75** rating (Pack Saddle Peak 2007, Iron Mountain 2009).



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3-3.75 – There are multiple coalesced spots of red and gray trees across the landscape. This is an active, widespread outbreak. Successful, current season attacked (red) trees are obvious and widespread. Gray trees (old attacks) may also be present and mixed with the red trees (Steamboat Peak 2007; Gros Vente Range 2009). Landscapes display varying degrees of coalescence ranging from initial coalescence to almost complete coalescence and are captured under this system with a **3**, **3.25**, **3.5**, and **3.75** rating.



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4 (four) – Complete coalescence where essentially the entire whitebark pine overstory has been killed (Teton Wilderness 2007).



L. Lasley



J. Pargiter

5 (five) –6 (six)—The condition of the residual forest after a major outbreak; gray forests without red trees. Landscapes display varying degrees of residual green (live) overstory after a major outbreak. This rating system captures this variation with a **5** (left photo) **5.25**, **5.5**, **5.75** and **6** (right photo) rating. A 6 is a complete ghost forest where the entire whitebark pine overstory is gray and has been removed (Avalanche Peak 2007 and Absaroka Range 2009).



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Appendix B. Conditions affecting image quality

Sun glare. The time of day that an image was captured had a profound impact on the quality of the image and one's ability to accurately classify that given image. Early-morning hours result in large shadows and substantial glare due to low sun angle, making it difficult to acquire quality images. The lower quality of the early morning images is easily identified when examining the images collected in this inventory. In the worst cases, images captured early in the morning were not usable in this project, and therefore are not included as part of the photo documentation. The threshold at which we determined to use these lower quality early morning shots was driven in part by our need for spatial coverage of the entire whitebark pine distribution. Therefore, if the only photos that covered a given catchment were lower quality early-morning photos, we were compelled to use these photos. Fortunately, early on in the project, we realized the negative effects of sun glare associated with morning light, especially when shooting directly east into the morning sun; we made then a concerted effort to eliminate the negative impacts of time of day on image quality.

The seemingly obvious remedy for this issue would be to eliminate early morning flights. However, early mornings are typically the preferred time of day to fly a single-engine airplane for various reasons, including less turbulence, cooler weather which reduces engine overheating, and, most importantly, improved safety. Flying in the mornings avoids afternoon thundershowers and the resulting low ceiling and hazards that these conditions present in mountainous terrain. Understandably, the pilot was reluctant to eliminate the early flights so a compromise was reached. The compromise included starting our flights half an hour later and

the flightlines were redesigned to reduce the instance of shooting directly into the morning sun. Also, as we inventoried areas further from Jackson Hole airport, the longer “ferry times” resulted in starting the flightlines later in the day.

The flight days where morning light had the greatest impact on image quality were July 6, and 7, and include the Wyoming, Salt River, and Snake River ranges along with the Teton Wilderness. These flights were conducted before we implemented our improved methodology to reduce the negative impacts of early morning image acquisitions. On July 17, flights over the Teton Range had areas of significant sun glare and shadowing.

Reflections. One constraint to the collection of quality imagery for this project was that all of our photos were shot through the window, which sometimes resulted in reflections from the plane windows. Early on we evaluated the imagery and found reflections to be a major issue; we modified our methods to reduce this problem. We wore dark clothing in the plane, and a black cloth was draped behind the photographer and/or between the photographer and the window, to reduce reflection. These modifications greatly reduced reflections and feedback in the photos.

Flight height. For the most part, the photos that were taken closest to the ground have better image quality and the most detail (highest resolution). But the complex mountainous terrain of the GYE posed serious constraints that impact one's ability to safely acquire low-elevation overflights. For example, if the surrounding terrain consists of 4000 m mountains, then it is required that one fly at a height of approximately 4,500 m in order to

safely and comfortably clear the mountain peaks. Therefore, the photos that capture the lower elevation forest around 2500 m are noticeably inferior in quality to photos of forest at 3000 m that are captured at a closer distance. We modified our flightlines to reduce the negative effects of long distance photography by flying beside mountain ranges, where possible, instead of on top of these ranges. This proved to be an effective method in “basin and range” type mountains (i.e., ranges running north-south with valleys on each side). In these instances we designed the flightlines to run through the valleys offering a horizontal view of the mountain range instead of looking down at the mountains. However in areas like the Beartooth Range, which is dominated by high alpine plateaus that range between 2,700 to 3,000 m and are cut by deep canyons, this flightline modification was not a possibility; therefore we flew at a constant higher elevation over this type of terrain.

Using a zoom lens was another way we reduced the effects of long distance photography on image quality. But because we wanted to collect sub-watershed level data, zooming in was not always appropriate for capturing images at the desired scale and extent. Zoom lenses also increase the likelihood of image blurring; therefore these lenses were used sparingly and with caution.

Weather conditions. We were very fortunate in the summer of 2009 to have exceptional weather for collecting high-quality aerial imagery. Not only was the overall weather very conducive to flying, but the lack of forest fires and subsequent lack of smoke in the air provided clear days for acquiring the necessary imagery. July 14, 2009, however, was an exception. On this day we attempted to fly flightlines within Yellowstone National Park and

were faced with a very low ceiling and serious turbulence. Capturing good photos in these conditions proved impossible and therefore we aborted the mission.

Appendix C. Photography specifications

Photography Equipment and Setting: Identical cameras, lens and camera settings were used by both the right and left aerial observers.

Cameras: Nikon D5000 an advanced D-SLR with 12.3-megapixel image quality

Lenses: Nikkor AF-S DX Zoom-18-55mm f/3.5-5.6G ED II

Camera and Lens Settings: Cameras were set to the landscape mode and auto focus was set on the lenses. The majority of the photos were captured at a focal length of 18-24 mm.

GPS Geo-tagging: A GP-1 GPS unit which automatically identifies and records every image's latitude, longitude and altitude.

Photo Format: The image output was set to high quality Jpeg and Raw format with an image resolution of 4288 x 2848.

Appendix D. GIS and imagery deliverables

All GIS layers and aerial photos used to generate this report and associated maps are available for distribution. Below is a list and brief summary of the project deliverables and how these products can be used to further understand the status of whitebark pine forests of the GYE as a snapshot in time in the summer of 2009.

Aerial Photography- All of the 4,653 geo-tagged photos classified by mortality rating in both high- and low-resolution JPEG format are available.

KML Files- All flightlines, photo points (the point on the flightline where each photo was captured), and look-at points (the point on the ground where the camera and observer was looking) are available in KML format for use in Google Earth. Both the photo and look-at points include an associated low resolution, geo-tagged, mortality-rated photograph that is viewable in Google Earth. The look-at point photos also have a snapshot view that allows the user to double click on the associated point and view the location of that the photo on the landscape. These KML products allow the user to explore and “drill-down” into the project data and make his/her own assessment of the mortality for a given photo and associated sub-watershed.

By providing the user with the ability to examine each image, the reliability of a given mortality rating can be assessed based on the quality of the photography used to classify the mortality in that area. Because image quality varies greatly over the project area due to environmental factors, it is possible that a user may identify an area of poor image quality and/or limited photo-coverage and determine that he or she needs to take a closer look and ground truth the mortality mapping.

GIS Layers—All GIS layers associated with and used for the mortality maps with associated metadata are available.

Mortality Maps—Look-at, sub-watershed and distribution-wide maps are also available.