Robert E. Keane, USDA Forest Service, Intermountain Research Station, Intermountain Fire Sciences Laboratory, P.O. Box 8089, Missoula, Montana 59807

Penelope Morgan, Department of Forest Resources, University of Idaho, Moscow, Idaho 83843

and

James P. Menakis, USDA Forest Service, Intermountain Research Station, Intermountain Fire Sciences Laboratory, P.O. Box 8089, Missoula, Montana 59807

Landscape Assessment of the Decline of Whitebark Pine (*Pinus albicaulis*) in the Bob Marshall Wilderness Complex, Montana, USA

Abstract

Whitebark pine (*Pinus albicaulis*) provides important food for wildlife and important cover for snow retention and watershed protection in high-elevation ecosystems of the northwestern United States. In the northern Rocky Mountains, this species is being reduced at accelerated rates by blister rust (*Cronartium ribicola*), mountain pine beetle (*Dentroctonous ponderosae*), and advancing succession resulting from fire exclusion. This study evaluates the extent and severity of the decline of whitebark pine in the Bob Marshall Wilderness Complex (BMWC) of Montana. Results of an extensive field survey of various whitebark pine communities were used to evaluate past and current whitebark pine population levels. Satellite imagery (LANDSAT TM) data were used in conjuction with field data to classify 14 BMWC subalpine cover types and 3 forest decline classes to detect extent of whitebark mortality in the study area. Results indicate whitebark pine population levels are rapidly decreasing, mostly as a result of the exotic disease blister rust. Field results show 83% of the 2,503 sampled whitebark pine trees are infected with blister rust and an average of 33% of their crowns have been killed by the disease. Results of the satellite image classification show whitebark pine dominant on 56% of the 311,257 hectares comprising the BMWC subalpine analysis area. Subalpine fir dominated a high proportion (14%) of this landscape, about 7% greater than its historical landscape composition. Approximately 22% of this landscape containing whitebark pine is now experiencing high mortality and 39% is experiencing moderate mortality. Classification accuracy was 60% for the vegetation cover types and 78% for the forest decline classes.

Introduction

Whitebark pine (*Pinus albicaulis*) is an important species of northern Rocky Mountain high elevation forests. In Montana, Idaho and northwestern Wyoming, it has been an important component on about 10-15% of the forested landscape (Arno and Hoff 1989). Although it has limited use as a commercial timber species, whitebark pine produces seeds that are highly valued by many species of wildlife as an important source of food. These animals include black bears (*Ursus americanus*) and grizzly bears (*Ursus arctos horribilis*) (Kendall 1980, Mattson *et al.* 1991), red squirrels (*Tamiasciurus hudsonicus*) (Ferner 1974) and Clark's nutcrackers (*Nucifraga columbiana*) (Tomback 1982). The nutcracker plays an mutualistic role in the whitebark pine regeneration process because it is essentially the only dispersal vector for the heavy, wingless whitebark pine seed (Tomback 1982). Whitebark pine also protects snowpack in high elevation watersheds and delays snowmelt (Arno and Hoff 1989, Hann 1990).

Whitebark pine is rapidly decreasing in some subalpine landscapes in the northern and western part of its geographical range (Ciesla and Furniss 1986, Keane and Arno 1993, Arno 1986, Kendall and Arno 1990). This decline is a result of three factors acting separately or in concert: (1) mountain pine beetle (*Dendroctonus ponderosae*), (2) successional replacement by more shade tolerant conifers, and (3) white pine blister rust (*Cronartium ribicola*). Mountain pine beetle epidemics killed many mature whitebark pine trees during the 1940's (Baker *et al.* 1971). The successional replacement of whitebark pine by subalpine fir (*Abies lasiocarpa*) and Engelmann spruce (*Picea engelmannii*) is a process that is usually retarded by naturally occurring fires. However, 60 years of fire suppression combined with mountain pine beetle and blister rust attacks have allowed fir and spruce to become dominant in forests historically dominated by whitebark pine (Arno 1986). Blister rust, an exotic disease from Europe introduced in the western United States in 1910, is especially fatal to whitebark pine when compared to other 5-needle pines (Arno and Hoff 1989, Bedwell and Childs 1943, Bingham 1972, Hoff and MacDonald 1977, Hoff *et al.* 1980).

The extent and severity of whitebark pine's decline across its range are poorly documented. Whitebark pine's low economic importance coupled with its inaccessible habitat have contributed to a lack of inventory and research data for this species. Most information has been from casual site observations rather than from extensive scientific surveys or investigations across entire landscapes. This study was initiated to determine the status of whitebark pine populations across the Bob Marshall Wilderness Complex, a large wildland preserve in northwest Montana. Subalpine forest communities were intensively inventoried to develop a spatial classification of cover types and forest decline classes using data from satellite imagery.

Satellite imagery has been used to classify existing vegetation and evaluate forest damage. Identification of vegetation cover types is best accomplished using the visible, near-infrared and mid-infrared spectral region of solar radiation (Jensen 1986, Moore and Bauer 1990, Bolstad and Lillesand 1992). Defoliation by gypsy moth (*Lymantria dispar*) has been detected using LANDSAT Thematic Mapper (TM) and SPOT data (Joria and Ahern 1991, Ambrosia *et al.* 1990). Trees damaged by spruce budworm (*Choristoneura fumiferana*) have been mapped by Leckie and Ostaff (1988) using satellite imagery. Various types of remotely sensed imagery was used to document forest decline in Europe and the state of Vermont (Kenneweq 1989, Landauer 1989, Rock and Vogelmann 1989, Vogelmann and Rock 1986).

Spectral reflectance shifts markedly as a result of insect damage on balsam fir (*Abies balsamea*) and lodgepole pine (*Pinus contorta*) (Leckie *et al.* 1988, Ahern 1988). Stressed and dying trees show a difference in reflectance in the red, near-infrared and thermal region as compared with healthy trees (Ahern 1988, Rock *et al.* 1986, Puritch 1981, Rock and Vogelmann 1989). Spectral wavelengths most sensitive to the detection of foliage mortality seem to range from 500 nm to 660 nm and 770 nm to 1600 nm which approximately encompass TM bands 2-5 (Ahern 1988, Leckie *et al.* 1988, Joria and Ahern 1991). Wavelengths in mid-infrared and thermal regions (TM bands 7 and 6) have been used for forest damage detection with limited success (Leckie and Ostaff 1988). Wavelengths in these regions include emitted radiation and are used for mortality classification because they often detect woody debris accumulation such as dead snags and downed logs (Elvidge 1988).

Study Area

The Bob Marshall Wilderness Complex (BMWC) is a remote 600,000 hectare preserve in northwest Montana, USA, composed of the Great Bear, Bob Marshall and Scapegoat Wilderness Areas (Figure 1). This area consists of mountainous terrain dissected by major river drainages. Two periods of glaciation formed the rugged cirque and peak landscape and filled valley bottoms with loosely consolidated glacial outwash alluvium (Alt 1985, Deiss 1958). Parent material is mostly quartzite and argillite with alternating layers of limestone, mostly in the eastern portions (Alt 1985). The Continental Divide is a high mountain barrier that transects the wilderness creating a unique blend of climates and plant communities. The climate west of the divide is modified maritime with cool wet winters and short, warm-dry summers. Average annual precipitation ranges from 50 cm/year in the driest valleys to over 275 cm/year on the Swan Front (the westernmost mountain range). East-side climates are continental with widely fluctuating winter temperatures and warm dry summers. Consistent winds are common along the east side of the Continental Divide. Precipitation averages 40 cm/year in the valleys to 150 cm/year along the Sawtooth Range (Soil Conservation Service 1981).

Whitebark pine is a major seral species at elevations above 1,830 meters within the study area. It has the potential to dominate 35-45% of the subalpine landscape within the BMWC (Bain 1990). In the absence of disturbance, whitebark pine is eventually replaced by the more shade-tolerant subalpine fir and Engelmann spruce in most of the area but it can form nearly pure climax stands on some high, dry ridges and mountain tops (Pfister *et al.* 1977).

Fires were common on the BMWC landscape during the last four centuries. Ayres (1901) estimated 20-40% of BMWC's whitebark pine forests burned during 1860 to 1900. Large, stand-replacement fires are typical in the study area, especially in the whitebark pine zone (Losensky 1990). The great dispersal distances of the nutcracker allow whitebark pine a competitive advantage in colonizing large burns (Tomback *et al.* 1990). Also, Clark's nutcrackers prefer open, burned areas to cache whitebark pine seeds

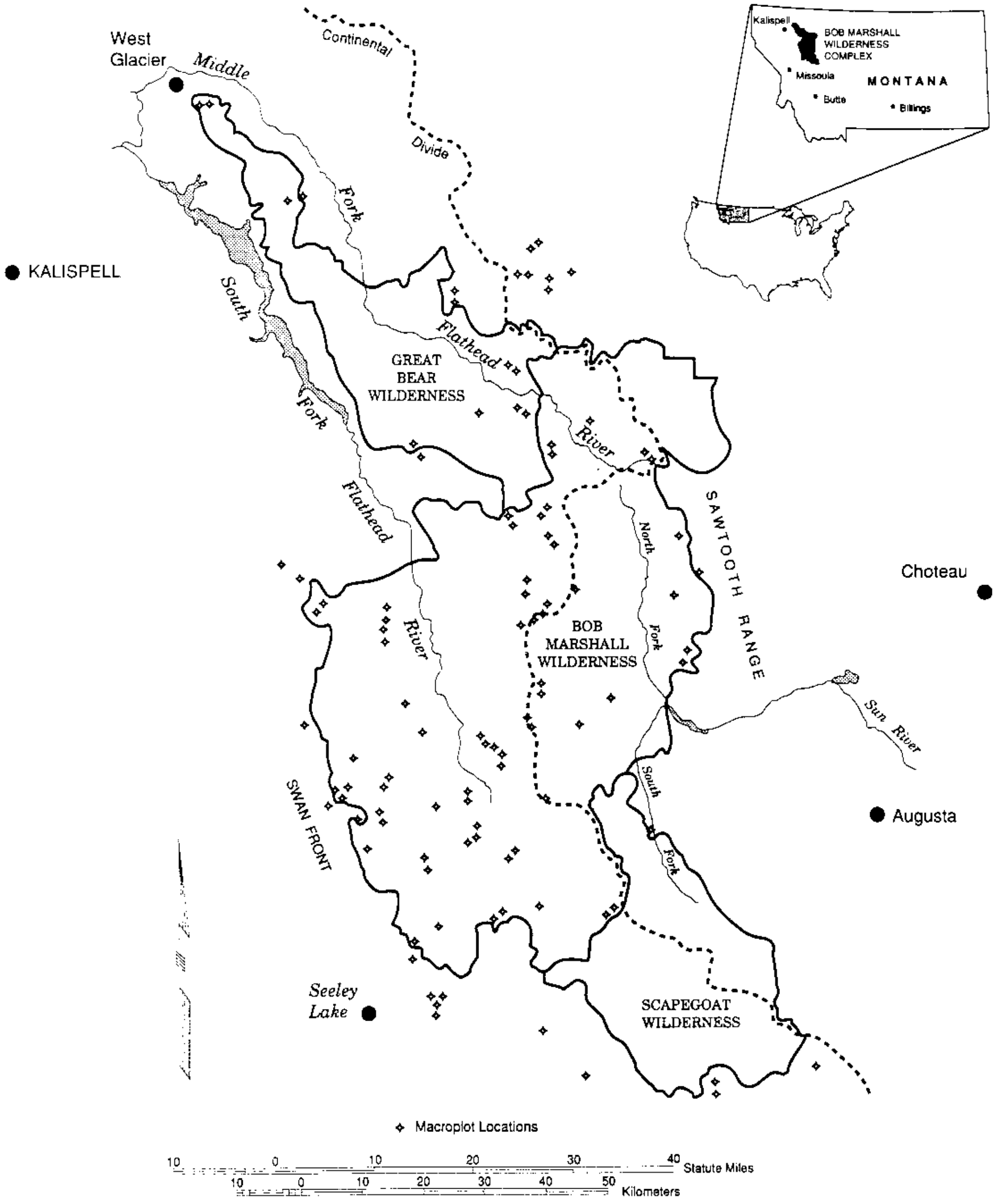

Figure 1. Map of the Bob Marshall Wilderness Complex in west-central Montana, USA with locations of macroplots sampled for this study.

(Tomback *et al.* 1990). Some whitebark pine stands in higher and drier areas of the southern portion of the BMWC contain evidence of less severe, more frequent surface fires (Gabriel 1976). These fires tend to kill mostly subalpine fir which favors the somewhat fire-resistant whitebark pine (Arno 1986). As a result, these fires maintain whitebark pine dominance and eliminate the subalpine fir understory (Arno and Hoff 1989).

Methods

Field Data Collection

A detailed ecological inventory was conducted in various whitebark pine stands across the entire BMWC and surrounding areas using ECODATA methodology (Keane *et al.* 1990, Hann *et al.* 1989). Circular 400 m^2 macroplots were located in representative portions of stands where whitebark pine had a density greater than 10 mature (greater than 15 cm diameter at breast height—DBH) trees per ha. Stand structure, fire history, fuels, topography, soils and plant community information were recorded at each macroplot. All trees greater than 2 cm DBH were sampled for age, size, and health. Fire scars on trees and tree ages were collected to obtain a fire history for the study area (Arno and Sneck 1977). Down, dead woody fuels (twigs, branches and logs) and organic matter (duff and litter) characteristics were inventoried about the macroplot using planar techniques (Brown 1974). Macroplots were geographically referenced using a Global Positioning System (GPS) to link these data to satellite imagery for development of spectral classifications.

Blister rust severity was evaluated for each whitebark pine tree as an estimation of (1) number of cankers per tree, (2) number of infected trees within the macroplot and (3) proportion of tree foliage killed by the rust. The number of cankers visible from the ground were estimated into broad classes (0 to 5, 5 to 10, and so on). The number of infected trees and the proportion of rust-killed foliage were ocularly estimated. Presence of mountain pine beetle was also recorded for each whitebark pine snag and living tree. Causes of mortality were estimated for dead trees when evidence existed.

Image Processing and Classification

Cover type and forest decline class for all BMWC subalpine and alpine areas were classified using satellite imagery in conjunction with digital terrain and environmental data (e.g., elevation, aspect, slope, estimated annual precipitation and vegetation type) (Figure 2). The GRASS spatial software package was used to analyze and classify the satellite imagery and manage the spatial data layers in a Geographic Information System (GIS) (USA CERL 1990). The Flathead and Lewis and Clark National Forests supplied many of the GIS layers used in TM classification analysis including previous vegetation classifications from LANDSAT Multispectral Scanner (MSS) scenes done in the late 1980's (Bain 1990).

A late summer 1990 September 3 LANDSAT Thematic Mapper (TM) scene (ID Y5237717443X0, Path 41, Row 27) was purchased for this classification effort. All seven spectral bands that comprised the TM scene were

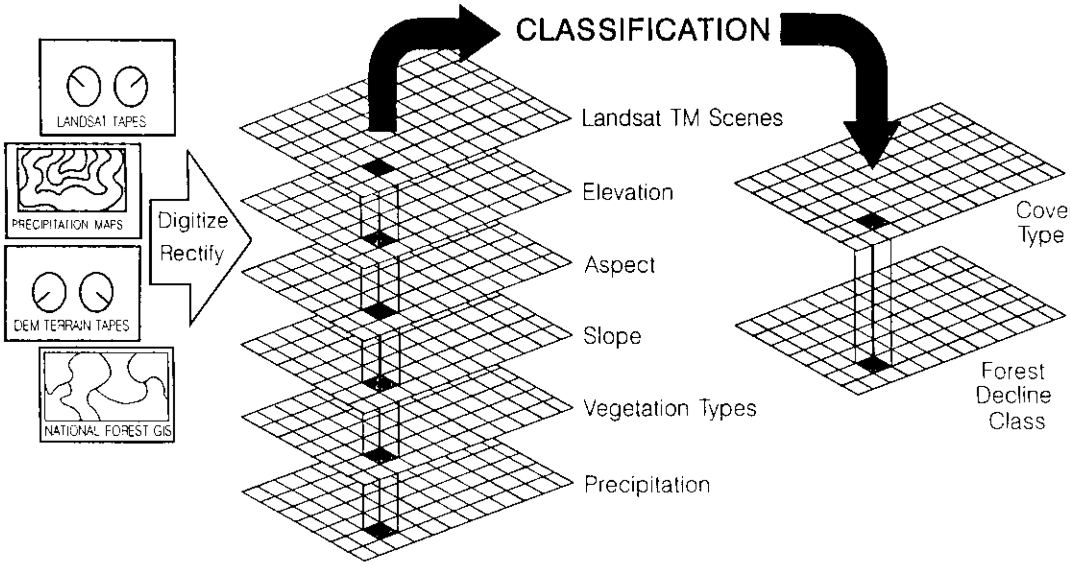

Figure 2. Procedure used to classify LANDSAT TM imagery to cover type and forest decline classes.

included in the analysis. A TM spectral band is composed of a matrix of 30 x 30 m pixels with each pixel's digital value representing the reflectance of light between a range of wavelengths integrated across the pixel area. However, the thermal TM band 6 had a pixel size of 120 x 120 m and detects mostly emitted radiation. TM band 7 also contains some emitted energy.

The TM scene needed some preprocessing before it was used to classify vegetation. First, all bands were geometrically rectified to the Flathead National Forest GIS layers using a coordinate transformation function in GRASS (i.rectify command) (RMS error = 19.46 meters or 0.65 pixel resolution). Next, the digital values for all seven bands of the TM scene were then radiometrically converted to radiance using gains and bias supplied by EOSAT (Price 1987, Leprieur *et al.* 1988). These radiance data were then corrected for haze and atmospheric effects (Jensen 1986) and included as layers in the BMWC GIS as supplied by the National Forests.

Many portions of the BMWC were excluded from the classification analysis. The TM scene covered only the central portion of the BMWC, missing most of the Scapegoat and Great Bear Wilderness areas (about 25% of the total BMWC land area). As a result, only areas within the boundaries of the BMWC and the image were considered in the classification analysis area. In addition, all areas below 1,830m in elevation, about 28% of the remaining analysis area, were excluded from the analysis because intensive field observations, including those from this study, indicate whitebark pine is seldom a major forest component below this elevation in the BMWC (Arno and Hoff 1989, Bain 1990, Pfister *et al.* 1977). Large geographic features such as lakes, marshes, ice and persistent snowfields delineated in the National Forests" GIS layers were also removed from the analysis (about 1% of the remaining BMWC analysis area). The final analysis area contained 51% of the total BMWC land area or 311,257 hectares and is shown in Figure 3.

Approximately 800 historical ECODATA macroplots that were used to develop past MSS vegetation classifications in the study area served as additional ground truth for this study's cover type classification. These macroplots were especially useful for characterizing those cover types that did not contain whitebark pine (Bain 1990). None of the historical ECODATA macroplots contained tree health or mortality information so they could not be used in the forest decline classification. Approximately 262 of the historical macroplots and 11 of this study's ECODATA macroplots were randomly excluded from the classification effort so they could be used as tests of the final classifications.

A preliminary cover type classification of all macroplots using the ECOPAC software package (Keane *et al.* 1990) identified 14 cover types and 3 forest decline classes important on the BMWC subalpine landscape. Gradient analysis techniques such as ordination with the programs TWINSPAN and DECORANA (Hill 1979a, Hill 1979b) were used as aids in the cover type classification effort (Gauch 1982). Environmental gradients interpreted from ordination results were used as guidelines for plot classifications. Plots were classified into cover types based mostly on the overstory dominance of tree species canopy cover. Cover types were named for the three dominant tree species in order of importance. For example, cover type 1 was dominanted by whitebark pine (30% canopy cover), with minor amounts of subalpine fir and Engelmann spruce (17 and 10%, respectively). Next, 110 macroplots were selected from all macroplots used in this classification to best represent every cover type and decline class on the ground. A minimum of 2 macroplots were used to represent each cover type, and a minimum of 20 macroplots represented each forest decline class. These selected macroplots then defined the training sites used in the TM scene supervised classification effort (Jensen 1986). Training sites are composed of a 3 x 3 pixel buffer around a central pixel that is the macroplot location. A digital color composite created from the TM spectral data was used to expand some training site boundaries. Macroplots not selected for use as training sites were used in the test of the TM classifications.

Supervised techniques were used to derive spectral signatures for the spatial classification of the TM scene from training site radiance values (Jensen 1986). Spectral signatures are composed of the mean values for each TM band and their associated variances and covariances computed across all pixels within a training site. Classified layers for cover and forest decline type were created by using the GRASS maximum likelihood algorithm (r.maxlik command) to classify each pixel from the spectral signatures of the training sites and the TM spectral data (USA CERL 1990).

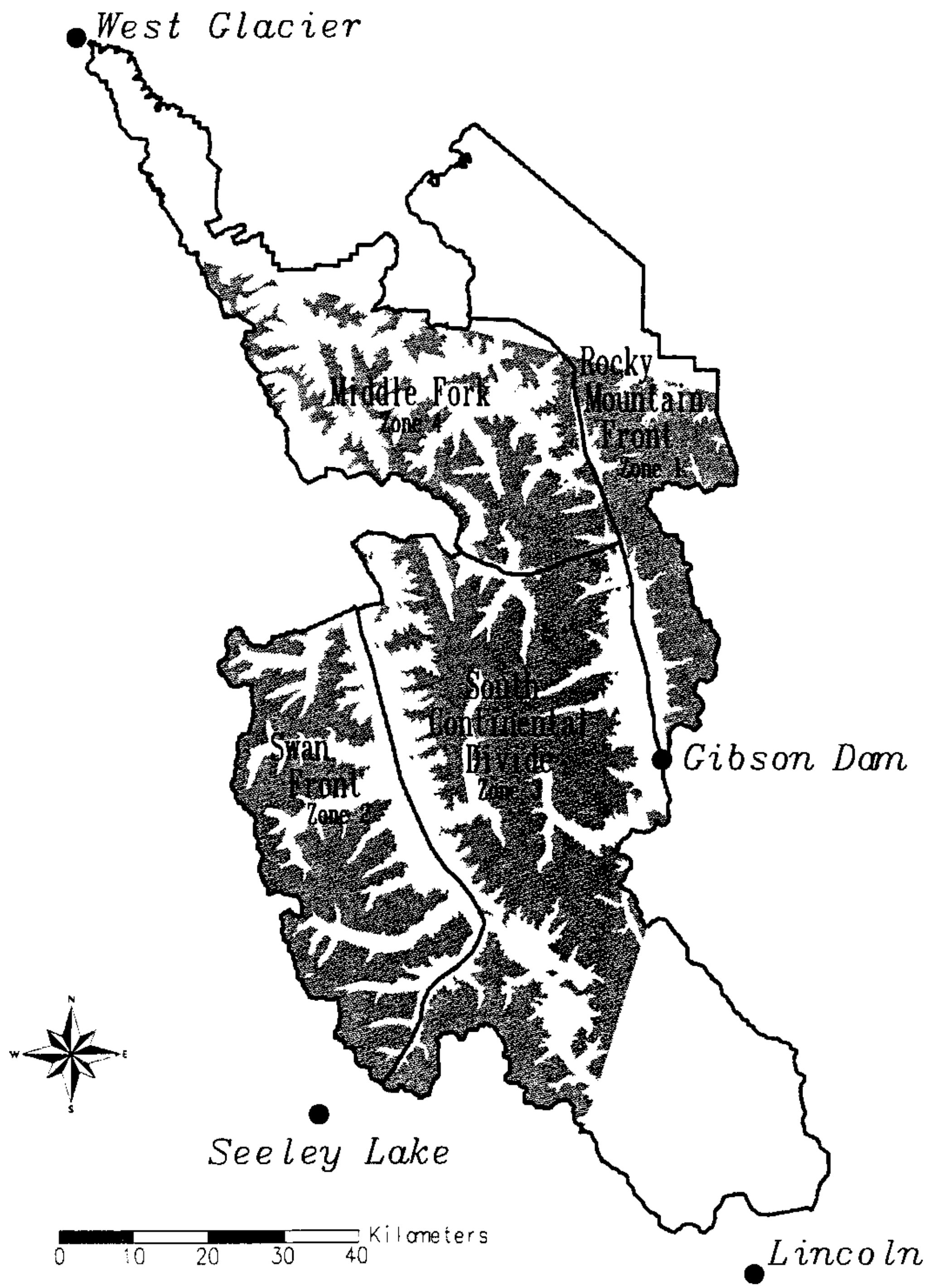

Figure 3. The BMWC image classification analysis area (shaded area). This portion of the study area includes only land covered by the TM scene that is above 1830 meters elevation. Also shown are the four BMWC geographical zones used to stratify research results.

These classified layers were then passed through a coarse-level filter to "smooth" the classification and remove "noise" generated from the input data and classification algorithm (Jensen 1986, Schowengerdt 1983). This filter was a 5 x 5 pixel window with the central pixel assigned a class value equal to the modal value of surrounding 24 pixels. The purpose of this low-pass filter was to achieve a minimum patch size of 0.1 ha commonly observed on the BMWC subalpine landscape.

Various combinations and transformations of the seven TM spectral bands were used to detect subtle characteristics in cover and forest decline type for the classification. Different combinations of TM bands (e.g., 3,4,5,7 is a TM band set) were used to achieve the best cover type and decline classification. Normalized difference vegetation index (NDVI) transformation was also included in TM band sets to distinguish cover type. NDVI is the ratio of the difference in band values and the sum of band values of the red and near infrared TM bands (Band 4 – Band 3 / Band 4 + Band 3) (Perry and Lautenschlager 1984, Jensen 1986). Principal Components Analysis (PCA) was performed on the seven TM bands using the GRASS software to reduce the dimensionality of the TM band set by compressing the information content of the seven bands into three principal component images (Jensen 1986, Schowengerdt 1983). Canonical Components Analysis (CCA) was also performed on TM bands 1-5 and 7. CCA is implemented in the GRASS program i.cca that takes the TM band data and a signature file containing the means and variance-covariance matrix of several training sites and creates transformed raster band files that provide maximum separability between training sites (USA CERL 1990). Three training sites from each of the identified 14 cover types were randomly selected for use in CCA transformation from the total of 110 possible training sites.

Elevation, aspect, slope and average annual precipitation spatial information from the GIS were used to refine the spectral classification of those pixels that were poorly classified based on a chi-square test of the classification results (Figure 2) (USA CERL 1990). Pixels not classified by the maximum likelihood algorithm to within a 20% chi-square confidence interval were then assessed for placement into another class based on topographical criteria taken from the macroplot data. A heuristic rule-based decision system that keyed cover type from the topographical and climate information was implemented for this effort using the GRASS command r.infer (USA CERL 1990). Relationships of classified cover types to topography and climate were taken from sampled macroplot information and ecological studies (Pfister *et al.* 1977, Arno and Hoff 1989). The previous MSS vegetation classification of the BMWC was also used in this classification's refinement to assess general trends of the poorly classified pixels. An ecological description of each classification category was summarized from the macroplot data using the ECOPAC software package (Keane *et al.* 1990). Characteristics that describe cover types or forest decline classes were computed as an average and range across all macroplots assigned to that class category (Jensen 1986). Only those areas classified to cover types containing whitebark pine were used to classify forest decline.

The final classified cover type layer was tested for accuracy after the filter smoothing using the ECODATA macroplots excluded from the classification effort. A 3 x 3 pixel boundary around each macroplot location was used as reference in the test procedure yielding nine test pixels per macroplot. The test involved overlaying the classified layer on the nine pixel macroplot reference stands to evaluate how the reference pixels matched the classified pixels. The same method was used to test the final forest decline classification but only the macroplot data taken for this study was used because historical macroplot information did not include adequate rust and tree mortality evaluations.

Results

Field Study

Over 2,500 whitebark pine trees were individually sampled from 111 whitebark pine stands established across the entire BMWC (Figure 1). Typically, sampled stands consisted of an overstory of old whitebark pine and spruce (20 to 500 trees/ha, 258 to 489 years of age) with an understory of almost exclusively subalpine fir (8 to 5,000+ trees/ha, 30 to 250 years of age). Only ten plots contained any whitebark pine regeneration (less than 50 years old). Whitebark pine snags were common ranging from 0 to 123 trees/ha. No evidence of extensive beetle epidemics was observed in the study area.

Blister rust is responsible for the majority of whitebark pine mortality in the BMWC. It was present in all but 3 of the 111 sampled stands. Blister rust had infected an average of 83% of the living whitebark pine trees and these trees had 10 to 15 cankers. An average of 33% of the crown of all living trees was killed by the rust. Field data suggest blister rust is prevalent over the entire BMWC with the highest incidences observed in the northern and western portions (Table 1). The southern portion of the Continental Divide in the BMWC seems to have lower blister rust severity.

TABLE 1. Field results of blister rust severity by geographical region within the study area. Severity is expressed as a percent of total live trees infected with rust, mean number of cankers per tree by class, and mean percent of crown killed by rust for whitebark pine trees on the macroplots.

Geographic region	Number plots	Percent trees infected	Average cankers/ tree	Percent crown kill
Swan Front	39	92	11-15	41*
Continental Divide	35	67*	6-10*	15*
Sawtooth Range	18	86*	11-15	33*
Middle Fork	19	93	11-15	48*
Averages	28	83	11-15	33

*Significant at p=0.05 using Kruskal-Wallis test across geographic region.

Fire history was difficult to determine in BMWC because of the rarity of fire-scarred trees in the whitebark pine zone. It appears stand-replacement wildfires killed most trees leaving few firescars on the landscape. However, an approximate fire history was determined from stand age structure and the few fire scars found. The estimated fire return interval for the entire study area was approximately 144 years with a minimum of 55 and a maximum of 304 years. This is comparable to Gabriel's (1976) findings for high elevation forests of the southern BMWC. Average stand age was approximately 228 years with the oldest stands exceeding 400 years.

Image Classification

Only one combination of the TM bands generated error rates lower than 50% for the cover type and forest decline classifications (Bands 1-7 in Table 2). Overall error rates and KHAT statistics (measure of overall agreement) (Congalton 1991) indicate no particular band combination generated a superior classification. Rather, the use of all TM bands resulted in the best classifications (Table 2). Classification success was not improved when the NDVI transformation was included in the band combinations. Principal Components Analysis (PCA) explained most of the variation (91%) in the seven TM bands into three component images that were included as new layers in the GIS (Layers A, B, C in Table 2). These layers were also included in the classification effort with limited success. The four new layers generated from Canonical Components Analysis (CCA) also yielded

TABLE 2. Overall classification accuracy of evaluated TM band combinations and transformations before filtering and smoothing.

TM Band Combinations	Cover Type Classification Overall Accuracy (%)	KHAT Accuracy (%)	Forest Decline Classification Overall Accuracy (%)	KHAT Accuracy
2,3,4,5	34.2	24.8	47.0	29.2
2,4,5,7	28.8	18.8	43.3	23.5
3,4,5,6	33.7	24.3	52.7	36.6
3,4,5,6,7	44.6	36.3	54.2	38.3
1,3,5,7, NDVI	27.6	17.6	47.2	29.6
3,4,5, NDVI	21.4	11.2	43.4	24.9
1,3,4,5,7	36.3	26.8	50.3	33.0
1,2,3,5,7	32.6	23.2	48.7	32.2
1,2,3,4,5,7	27.1	18.4	54.5	38.0
1,2,3,4,5,6,7	56.5	49.0	70.4	56.6
PCA - A,B,C*	28.0	17.7	45.0	21.8
CCA - A,B,C,D*	42.0	32.5	48.3	25.1

*A,B,C,D are transformations of TM bands 1-7 high error rates when used in cover type classification (Table 2). In general, TM bands 3,4,5 were useful in cover type classification while bands in the infrared and thermal regions (bands 4-7) were best for forest decline classification.

Fourteen cover types were spatially classified from all seven TM spectral bands and added as a layer in the BMWC GIS (Table 3). The northern portions of the BMWC (Middle Fork zone) seem to be dominated by subalpine fir (19% of landscape) while the southern portions (southern Continental Divide) are dominated by whitebark pine (64%). Topographical and vegetation characteristics summarized from the macroplot data are shown for all cover types in Table 4. The lack of data for some cover types in Table 4 is because the macroplot data for those types were taken by the National Forest personnel and detailed tree and fuel information were not recorded (Bain 1990). The error matrix for the final cover type classification shows 60% overall accuracy and 52% KHAT accuracy (Table 5).

The forest decline classification used TM bands 3 to 7 to predict extent of whitebark pine decline in the BMWC (Table 6). Forest decline was rated to three broad mortality classes of low, moderate and high based on the health of whitebark pine and density of standing dead trees (Table 7). Results of the imagery classification seem to agree with the field results with the Swan Front and Middle Fork zones experiencing the greatest decline (26 and 24% in high decline class, respectively) (Table 6). The lowest levels of mortality appear to be along the Sawtooth Range and Southern Continental Divide where 82% and 78% of the forested area is in the low to moderate decline class. Classification accuracy averaged 78% overall with a 68% KHAT accuracy (Table 8).

The spatial extent of cover types by decline class is shown in Table 9. Whitebark pine dominated stands (cover types 1,3,5,6,7) comprise the majority of subalpine land area in the BMWC (56%). Nonforest cover types (shrubs, herbs, rocks) occupy about 28% of the analysis area. Only about 15% of this nonforested area is capable of supporting trees as estimated from the macroplot data collected by the Flathead National Forest personnel. Cover types where subalpine fir is dominant (types 2,4,8) have the highest proportion of their land area in the high decline class. The whitebark pine-lodgepole pine cover type and the high elevation cover types with alpine larch (cover types 5-8) have the greatest portion of land in the low decline class.

TABLE 3. Land area summary (hectares) of the classified cover type by four BMWC geographic zones. Numbers in parenthesis are the percent of cover type within that geographic zone.

		BMWC Geographic Zones								
Classified Cover Types Num	Name	Sawtooth Range 1		Swan Front 2		S. Cont Divide 3		Middle Fork 4		Totals
1	PIAL-ABLA-PIEN	17,816	(41)	30,386	(42)	65,980	(48)	22,747	(39)	136,929
2	ABLA-PIEN-PIAL	2,145	(5)	4,467	(6)	8,533	(6)	3,838	(7)	18,983
3	PIAL-PICO-ABLA	1,440	(3)	2,930	(4)	10,397	(8)	2,143	(4)	16,910
4	ABLA-PIAL-PICO	0	(0)	27	(>1)	26	(>1)	9	(>1)	62
5	PIAL-PICO	1,806	(4)	4,443	(6)	10,755	(8)	1,895	(3)	18,899
6	PIAL-LALY-ABLA	34	(>1)	25	(>1)	58	(>1)	109	(>1)	226
7	PIAL-LALY	97	(>1)	1,897	(3)	972	(1)	1,101	(2)	4,067
8	ABLA-PIAL-LALY	85	(>1)	253	(>1)	262	(>1)	139	(>1)	738
9	PICO-ABLA	319	(1)	799	(1)	1,451	(1)	928	(2)	3,497
10	ABLA-PIEN	1,656	(4)	5,881	(8)	3,434	(2)	6,956	(12)	17,927
11	PICO	406	(1)	1,398	(2)	4,539	(3)	453	(1)	6,796
12	Shrubs	3,014	(7)	8,634	(12)	8,057	(6)	8,677	(15)	28,382
13	Herbs	4,357	(10)	4,560	(6)	7,542	(6)	4,209	(7)	20,668
14	Rock, Soil	10,561	(24)	7,207	(10)	14,701	(11)	4,705	(8)	37,174
Totals		43,735		72,907		136,706		57,909		311,257

*PIAL–*Pinus albicaulis*, ABLA–*Aies lasiocarpa*, PIEN–*Picea engelmannii*, PICO–*Pinus contorta*, LALY–*Larixlyalli*

TABLE 4. Ecological characteristics of classified cover types for the BMWC subalpine landscape. These values are computed as a mean across all macroplots within a sampled cover type.

	Cover Type Number[2]													
Characteristic	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Cover type name[1]														
Dominant species	PIAL	ABLA	PIAL	ABLA	PIAL	PIAL	PIAL	ABLA	PICO	ABLA	PICO	SHRUB	HERB	ROCK
Secondary species	ABLA	PIEN	PICO	PIAL	PICO	LALY	LALY	PIAL	ABLA	PIEN				SOIL
Tertiary species	PIEN	PIAL	ABLA	PICO		ABLA		LALY						
Number Macroplots	50	31	14	2	9	2	2	2	5	50	5	50	50	50
Stand age (yr)	307	250	200	372	202	271	257	294	96	–	94	–	–	–[3]
Whitebark pine–PIAL														
Cover (%)	30	17	19	11	28	20	25	10	1	2	1	4	2	0
Overstory age (yr)	257	229	199	284	209	171	175	286	–	–	–	–	–	–
Understory age (yr)	79	92	74	74	93	91	82	48	–	–	–	–	–	–
Understory density (trees/ha)	300	160	138	7	91	3	35	15	–	–	–	–	–	–
Standing Dead														
Basal area (m2/ha)	9.18	9.48	5.46	17.6	3.70	6.66	1.12	5.16	–	–	–	–	–	–
Density (trees/ha)	180	185	163	321	106	49	12	99	–	–	–	–	–	–
Rust severity														
Percent infection	82.1	87.6	84.9	70.8	79.0	79.0	50.0	100.0	–	–	–	–	–	–
Cankers/tree	10-15	15-20	10-15	10-15	10-15	5-10	10-15	10-15	–	–	–	–	–	–
Rust crown kill (%)	27.1	35.2	40.2	29.8	36.6	11.9	19.5	34.2	–	–	–	–	–	–
Subalpine fir–ABLA														
Cover (%)	17	26	13	30	5	20	6	15	10	30	1	8	3	0
Overstory age (yr)	170	157	96	159	135	240	101	–	–	–	–	–	–	–
Understory age (yr)	120	106	107	85	79	67	78	114	–	–	–	–	–	–
Understory density (trees/ha)	1960	1185	286	145	20	49	74	72	–	–	–	–	–	–
Engelmann spruce–PIEN														
Cover (%)	10	20	8	7	2	0	0	3	10	1	1	1	3	2
Overstory age (yr)	220	236	204	314	136	–	249	–	–	–	–	–	–	–
Understory age (yr)	108	69	91	84	55	–	–	–	–	–	–	–	–	–
Understory density (trees/ha)	311	195	106	15	10	0	15	0	–	–	–	–	–	–
Lodgepole pine–PICO														
Cover (%)	1	2	22	11	16	0	0	0	54	3	60	5	2	0
Alpine larch–LALY														
Cover (%)	1	0	0	0	0	20	20	10	0	0	0	0	0	0
Rock Cover (%)	12	15	15	20	31	14	5	8	2	7	25	13	25	60
Shrub Cover (%)	60	52	70	45	46	60	75	75	52	57	40	53	11	–
Herbaceous cover (%)	47	52	28	32	30	60	41	40	26	65	17	68	74	–
Elevation (m)														
Minimum	1927	1963	1961	2061	2030	2400	2376	2300	1927	1944	1919	1944	1997	–
Maximum	2490	2417	2332	2128	2445	2400	2384	2395	1859	1853	1829	1856	1853	–
Mean	2190	2170	2110	2090	2240	2400	2380	2350	2037	2164	2018	2195	2225	–
General Aspect	SE-SW	SE-SW	SE-SW	NE-SE	SE-SW	SW-NW	NW-NE	NW-NE	SE-NW	NE-SW	NE-SW	NE-SW	NE-SW	–
Slope (%)	34	31	31	20	33	42	29	46	27	37	50	27	25	–
Woody Fuel (kg/m²)														
0 to 1 cm dia	0.02	0.01	0.02	0.00	0.01	0.00	0.02	0.00	–	–	–	–	–	–
1 to 3 cm dia	0.11	0.06	0.01	0.22	0.22	0.22	0.25	0.18	–	–	–	–	–	–
3 to 7.6 cm dia	0.36	0.29	0.25	0.22	0.22	0.22	0.25	0.63	–	–	–	–	–	–
7.6+ cm dia	3.23	2.06	1.34	1.34	2.26	2.10	3.60	2.22	–	–	–	–	–	–

[1] PIAL–*Pinus albicaulis*, ABLA–*Abies lasiocarpa*, PIEN–*Picea engelmannii*, PICO–*Pinus contorta*, LALY–*Larix lyallii*

[2] Cover types 1-8 are described by data gathered in this study, cover types 9-13 are described by historical macroplot data gathered by the Flathead National Forest, cover type 14 (Rock) was described from photos.

[3] The symbol '–' denotes no data were available to compute average values

[4] SW–Southwest, SE–Southeast, NW–Northwest, NE–Northeast

TABLE 5. Error matrix comparing the agreement between ground truth pixels and the BMWC cover type classification. Overall accuracy was 60.1% and the KHAT accuracy was 51.9%.

Reference Cover Types	Classified Cover Types 1	2	3	4	5	6	7	8	9	10	11	12	13	14	Tot	Commission[1] Error (%)
1	398	28	14	0	4	0	9	0	0	22	2	77	54	14	622	37
2	122	153	11	0	0	0	0	0	1	53	0	36	26	0	402	62
3	19	5	60	0	5	0	5	0	2	3	9	17	0	0	125	52
4	9	0	0	5	0	0	0	0	0	0	0	13	0	0	27	82
5	2	0	0	0	68	0	0	0	0	0	0	2	0	0	72	6
6	10	0	0	0	0	4	15	0	0	1	0	14	1	0	45	92
7	0	0	0	0	0	0	14	0	0	0	0	0	0	0	14	0
8	18	0	0	0	0	0	0	18	0	0	0	0	0	0	36	50
9	8	0	10	0	0	0	0	0	18	0	0	0	0	0	36	50
10	30	0	0	0	0	0	0	0	0	45	5	27	9	0	116	62
11	1	7	0	0	0	0	0	0	0	0	27	0	0	0	35	23
12	26	14	0	4	34	0	1	0	0	0	0	99	17	9	204	52
13	32	2	0	0	15	0	0	0	0	0	0	40	126	41	256	51
14	22	0	0	0	13	0	0	1	0	3	0	0	10	418	478	11
Total	697	209	95	9	139	4	44	19	21	127	43	325	243	482	2457	40
Omission[1] Error	43	27	37	45	52	0	69	6	15	65	38	70	49	14	40	

[1] Commission error is the error of misclassifying a reference stand and Omission error is the error of not classifying the cover type correctly.

TABLE 6. Land area summary of classified forest decline classes for the cover types containing whitebark pine by the four BMWC geographic zones. Numbers in parenthesis indicate the proportion of the decline class within that geographic zone.

Classified Decline Class Num	Name	BMWC Geographic Zones Sawtooth Range		Swan Front		South Cont Div		Middle Fork		Totals	
1	Low	8,822	(38)	18,309	(41)	36,899	(38)	11,652	(36)	75,682	(39)
2	Moderate	10,323	(44)	14,802	(33)	39,152	(40)	12,799	(40)	77,076	(39)
3	High	4,277	(18)	11,317	(26)	20,932	(22)	7,530	(24)	44,056	(22)
Totals		23,422	(12)	44.428	(22)	96.983	(50)	31,981	(16)	196,814	

TABLE 7. Forest decline characteristics for BMWC whitebark pine stands.

Stand Characteristic	Forest Decline Class Low	Moderate	High
Trees infected with rust	0 to 50%	51% to 90%	91% to 100%
Crown foliage killed	0 to 10%	11% to 40%	41% to 100%
Snag density (trees/ha)	0 to 10	10 to 50	>50

TABLE 8. Error matrix contrasting the agreement between ground truth pixels and the forest decline classification. Overall accuracy was 78.4% and KHAT accuracy was 67.8%.

Reference Decline Class	Classified Decline Class Low	Mod	High	Totals	Commission Error (%)
Low	177	19	13	209	16
Mod	27	167	53	247	33
High	24	7	176	207	15
Totals	228	193	242	663	22
Omission Error (%)	23	14	28	22	

TABLE 9. Land area in hectares by classified cover type and forest decline class for the BMWC analysis area. Percent of forest decline class within a cover type are provided in parenthesis. Some cover types (9-14) did not have significant amounts of whitebark pine so no estimate by forest decline class was needed. Snow, ice and water were excluded from the analysis area.

Cover Type Num	Name	Forest Decline Class Low		Moderate		High		Total Land Area hectares	%
1	PIAL-ABLA-PIEN	49,030	(36)	60,491	(44)	27,408	(20)	136,929	44
2	ABLA-PIEN-PIAL	5,584	(30)	5,342	(28)	7,804	(42)	18,983	6
3	PIAL-PICO-ABLA	3,246	(19)	9,526	(56)	4,138	(25)	16,910	5
4	ABLA-PIAL-PICO	7	(12)	1	(1)	54	(87)	62	>1
5	PIAL-PICO	13,083	(69)	1,626	(9)	4,190	(22)	18,899	6
6	PIAL-LALY-ABLA	217	(96)	7	(3)	2	(1)	226	>1
7	PIAL-LALY	3,994	(98)	71	(2)	2	(0)	4,067	1
8	ABLA-PIAL-LALY	521	(70)	12	(2)	207	(28)	738	>1
9	PICO-ABLA	0	0	0	0	0	0	3,497	1
10	ABLA-PIEN	0	0	0	0	0	0	17,927	6
11	PICO	0	0	0	0	0	0	6,796	2
12	Shrubs	0	0	0	0	0	0	28,382	9
13	Herbs	0	0	0	0	0	0	20,668	7
14	Rock, Soil	0	0	0	0	0	0	37,174	12
Totals		75,676	(39)	77,080	(39)	44,058	(22)	31,125	100

Discussion

Status of Whitebark Pine

Whitebark pine is rapidly declining in the BMWC, and the obvious causes are blister rust and successional replacement. There are very few areas in the BMWC where rust has not infected whitebark pine trees. It appears the rust epidemic is extensive with the majority of the forested analysis area (61%) in the moderate and high decline class (Table 9). A 1991-92 remeasurement of whitebark pine trees in historical plots located around western Montana first measured in 1971 indicate that approximately 2% of the species" basal area and 3% of its trees are lost each year (Keane and Arno 1993). At this rate it is estimated that most BMWC whitebark pine stands will move from the moderate to high decline class within about a decade. There is ample evidence from macroplot data that whitebark pine had been experiencing mortality for some time. There are many standing and fallen dead whitebark pine trees at most sites (Table 4) and it is estimated that most of these trees were killed by the rust.

It appears that the whitebark cone crop in the BMWC has greatly decreased. Field results show that about a third of all whitebark pine crowns are now dead. Blister rust typically begins killing a tree by infecting and girdling the top of the crown, then spreading downwards on the trunk and eventually girdling the entire tree. Nearly all whitebark pine cones are produced in the upper third of the crown that is killed first by the rust. With 83% of whitebark pine trees infected and 61% of the analysis area in the moderate or high decline class, it seems the potential for the large cone crops that were historically common in BMWC subalpine forests (Cheff 1984) has been greatly reduced.

Historical stand structure and composition estimated from the macroplot data indicate that the majority of BMWC subalpine forests were, until recently, dominated by whitebark pine with a small component of subalpine fir and spruce in the overstory (Keane and Morgan 1994). Presence of an older age class of whitebark pine and the preponderance of whitebark pine snags indicate that these stands once supported about 20-30 m^2/ha^{-1} of whitebark pine and very little subalpine fir. Now, subalpine fir is abundant in both the understory and overstory because of this rapid mortality in whitebark pine (Table 4). This is evident from TM classification results considering cover types dominated by subalpine fir (cover types 2,4,8) have the highest proportion of their land area in the high decline class because blister rust-caused mortality of whitebark pine is accelerating succession to subalpine fir. In addition, approximately 14% of the forested BMWC subalpine landscape is dominated by fir and spruce (cover types 2,4,8,10 in Table 9). This seems higher than historical percentages considering the mean pre-1900 fire return interval (144 years estimated from this study) is less than the time it takes for subalpine fir to become dominant in the overstory (150 to 250 years estimated from data used in Table 4). Moreover, Ayers' (1901) estimate of 20 to 40% land area burned every 40 years would indicate that only a small portion of the BMWC landscape would be greater than 150 years old.

The exclusion of most fires on these landscapes over the last 60 years has also possibly contributed to a marked increase of subalpine fir both in the understory (PIAL-ABLA-PIEN cover type 1) and overstory (ABLA dominated cover types 2,4,8,10) (Table 4). This agrees with Arno (1986) and Kendall and Arno (1990) that whitebark pine is being successionally replaced by the more shade-tolerant fir and spruce. Arno *et al.* (1993) found 14% of their study area in the Bitterroot Mountains of Montana was dominated by whitebark pine in the early 1900's and none of that area was dominated by whitebark pine in 1991. Without fire, the shade-intolerant whitebark pine has limited success regenerating under closed canopies. The lack of whitebark pine regeneration in the sampled stands (Table 4) again suggests that the species will eventually be replaced by subalpine fir and spruce in the absence of fire.

This field study and Ayres' (1901) survey indicate that fires were important on the BMWC subalpine landscape. Fires that started during non-extreme weather years in the southern BMWC were rarely large and usually consumed scattered surface fuels (Arno 1986, Gabriel 1976). However, these surface fires tended to kill the fire-intolerant fir, spruce and young whitebark, but larger whitebark pine trees survived. This type of fire regime, although rare in the BMWC, maintained open, park-like stands of nearly pure whitebark pine (Arno 1986). Some stands of cover type 1 (PIAL-ABLA-PIEN) closely resemble this historical stand character except for the high coverage of fir and spruce which is perhaps linked to rust mortality and fire exclusion (Table 4). Extensive, stand-replacement fires such as those documented by Ayres (1901) and Losensky (1990) created burned areas heavily colonized by whitebark pine regeneration from nutcracker-cached seed. These large fires were probably a result of extreme dry, windy weather conditions and prolonged drought (Losensky 1990).

Blister rust severity seems to be related to geographic region within the BMWC. Results of both the field study (Table 1) and image classification (Table 6) indicate that whitebark pine mortality is higher in the northern and western portions of the wilderness. Stands near the Continental Divide in the southern BMWC tend to have less rust damage. This phenomenon may be related to climatic conditions during rust spore transport from the alternate host *Ribes* spp. (currant and gooseberry shrubs) to whitebark pine during late summer and early fall. Successful spore germination and infection requires warm, moist environments (Bingham 1972). Although these conditions occur infrequently in high elevation areas, they are more frequent in the modified-maritime climates of the northern and western BMWC than the southern portion of the area (Keane and Morgan 1994).

Image Classification

Accurate classification of BMWC subalpine cover types proved to be quite difficult. Past fire history, heterogeneous stand structure, similarity of cover types and varying soil parent material confounded classification results. Field sampling did not adequately cover the full range of successional community types for all subalpine cover types. Moreover, most BMWC subalpine forests are quite open, averaging 20 to 40% tree canopy cover with the understory mostly composed of shrubs and herbs (Table 4). The LANDSAT TM scanner estimates average spectral reflectance across a 30 meter square pixel. Therefore, the spectral signal from the open forested BMWC subalpine cover types were often confused with the signal from shrub and herb communities (Table 4). The opposite was also true. A high similarity of tree species across cover types also served to weaken the classification. Distinctions between some cover types were subtle and these similar types may be merged in the future. Lastly, subalpine community composition differed across limestone and non-limestone substrates resulting in limited success in using topographic rules to predict cover types without a soil layer in the GIS.

Shadowing in the LANDSAT TM scene also reduced classification accuracy. The sun elevation angle of 44 degrees and azimuth of 140 degrees resulted in extensive shadow across this topographically complex area. Fortunately, shadowing was not as severe in the high elevation areas, but many steep, subalpine north slopes were in some shadow which influenced classification results.

Inaccurate historical ECODATA macroplot locations caused high classification error rates. Macroplots established for this study were accurately located to within 10-30 meters using GPS instruments. However, the historical macroplots established for other classification efforts used USGS topographic maps and aerial photos to estimate spatial coordinates (Bain 1990). These historical locations were sometimes off by 100-200 meters. The overall accuracy increased from 60 to 83% when only plots from this study were used to test cover type classification (Table 10). However, this study located plots only in cover types that contained whitebark pine.

The forest decline classes were designed to recognize broad assessments of the amount of dead and dying whitebark pine on the BMWC landscape. Since blister rust is the major cause of this mortality, it was assumed that these classes would be related to blister rust severity. However, there probably were other situations that would give the same decline classes. For example, we noticed, but did not sample, abundant subalpine fir mortality in some portions of the northern BMWC that were classified to the high forest decline class. This is a situation where the majority of mortality is from subalpine fir rather than whitebark pine. The Gates Park fire of 1988 in the northern Sun River drainage (Figure 1) killed nearly all subalpine trees within its boundaries. This area was classified to the high decline class because of the great amount of fire-killed trees, not because of high blister rust mortality.

TABLE 10. Error matrix using only ECODATA plots geographically located with GPS. Overall accuracy 83.5% and KHAT accuracy was 75.2%.

Reference	Classified Cover Type									Commission
Cover Type	1	2	3	4	5	6	7	8	Totals	Error (%)
1	323	16	7	0	1	0	0	0	347	7
2	61	111	6	0	0	0	0	0	178	38
3	6	5	58	0	5	0	5	0	79	27
4	0	0	0	5	0	0	0	0	5	0
5	2	0	0	0	68	0	0	0	70	3
6	5	0	0	0	0	4	0	0	9	56
7	0	0	0	0	0	0	14	0	14	0
8	0	0	0	0	0	0	0	18	18	0
Totals	397	132	71	5	74	4	19	18	720	17
Omission Error (%)	19	16	19	0	9	0	27	0	17	

Implications of Whitebark Pine Decline

The consequences of whitebark pine decline in the BMWC could be devastating for some animal and plant species. The BMWC is one of the few remaining ecosystems with substantial numbers of grizzly bears that historically depended on abundant whitebark pine cone crops (Craighead *et al.* 1982). As the cone crops dwindle, bears must either migrate or find a new source of prehibernation foodstuffs (Mattson *et al.* 1991, Kendall 1980). Squirrels and Clark's nutcrackers will also need to find alternate food sources, as will those animals that depend on them (Ferner 1974). Moreover, the Clark's nutcracker will tend to eat proportionally more seeds when the available seed supply is low (Tomback 1982). Therefore, whitebark regeneration potential will be somewhat reduced because fewer seeds will be cached and most of the seeds cached will probably be excavated. Shifts in vegetation composition and wildlife migration as whitebark pine declines can invoke major changes in the diversity and structure of the subalpine landscape.

An important step towards sustainable management of whitebark pine ecosystems is inventory. The extent and severity of whitebark pine decline is mostly unknown in the northwestern United States. Most western United States national parks have yet to identify the extent and condition of their whitebark pine forests (Kendall 1993). Very few high elevation forests are inventoried on national forests by the USDA Forest Service probably because they have little commercial value and are somewhat inaccessible. Identification of whitebark pine health and status on the regional landscape can provide important information for various projects such as rust-resistant breeding programs or grizzly bear relocation programs. It is also necessary for developing strategies for restoring whitebark pine across its range.

Conclusions

Blister rust is killing many whitebark pine trees across the BMWC. The heaviest mortality is occurring in the modified-maritime climates of the northern and western portions of the BMWC. The potential for large whitebark pine cone crops has been severely reduced because the rust tends to kill the cone-bearing branches first. This will affect the many animals that utilize whitebark pine seed.

Successional replacement of whitebark pine by subalpine fir and Engelmann spruce is also a major cause of whitebark pine decline. Policies of fire exclusion in the BMWC over most of the last 50-60 years has resulted in a high proportion of subalpine forest area dominated by subalpine fir and spruce. Moreover, those areas currently dominated by whitebark pine have an abundance of subalpine fir in the understory. Lastly, the high rust-caused mortality in whitebark pine has accelerated succession to subalpine fir dominance.

Acknowledgements

We would like to thank Steve Arno, USDA Forest Service, Intermountain Research Station, for consultation and manuscript review; Wendel Hann, USDA Forest Service, Northern Region Ecosystem Management Project, for project support; the Flathead and Lewis and Clark National Forests for assistance in both field and GIS data collection; and Tom Cook, USDA Forest Service, Northern Region Aviation and Fire Management, for digitizing training areas.

Literature Cited

Ahern, F. J. 1988. The effects of bark beetle stress on the foliar spectral reflectance of lodgepole pine. Int. J. Remote Sensing. 9(9):1451-1468.

Alt, D. 1985. Geology of the Bob Marshall. *In* Montana's Bob Marshall Country by R. Craetz. Montana Magazine, Inc., Helena, Montana. Pp. 9-19.

Ambrosia, V. G., J. S. Myers, M. T. Fitzgerald, and W. Clerke. 1990. Detection of gypsy moth infestation and defoliation from airborne thematic simulator data. *In* Protecting Natural Resources with Remote Sensing—The third Forest Service remote sensing applications conference. Univ. Arizona, Tucson. April 9-13, 1990. Pp. 108-119.

Arno, S. F. 1986. Whitebark pine cone crops: a diminishing source of wildlife food? W. J. Appl. For. 1(3):92-94.

Arno, S. F., and R. J. Hoff. 1989. Silvics of whitebark pine (*Pinus albicaulis*). USDA For. Serv. Gen. Tech. Rep. INT-253. 11 p.

Arno, S. F., E. D. Reinhardt, and J. H. Scott. 1993. Forest structure and landscape patterns in the subalpine lodgepole pine type: A procedure for quantifying past and present conditions. USDA For. Serv. Gen. Tech. Rep. INT-294. 17 p.

Arno, S. F., and K. M. Sneck. 1977. A method for determining fire history in coniferous forests of the Mountain West. USDA For. Serv. Gen. Tech. Rep. INT-42. 28 p.

Ayres, H. B. 1901. Lewis and Clark Forest Reserve, Montana. 21st Ann. Report US Geol. Survey, Part 5:27-80.

Bain. S. 1990. LANDSAT classification and field correlation methods for vegetation classification used at the Flathead National Forest. *In* Proceedings, Land classification based on vegetation: applications for resource management, D. E. Ferguson. P. Morgan, and F. D. Johnson, Compilers. Nov. 17-19, Moscow, Idaho, 1987. USDA For. Serv. Gen. Tech. Rep. INT-257. Pp. 255-258.

Baker, B. H., G. D. Amman, and G. C. Trostle. 1971. Does the mountain pine beetle change hosts in mixed lodgepole and whitebark pine stands? USDA For. Serv. Res. Note INT-151. 7 p.

Bedwell, J. L., and T. W. Childs. 1943. Susceptibility of whitebark pine to blister rust in the Pacific Northwest. J. For. 41:904-912.

Bingham, R. T. 1972. Taxonomy, crossability, and relative blister rust resistance of 5-needled white pines. In Biology of rust resistance in forest trees. Misc. Pub. No. 1221. USDA: 271-280.

Bolstad. P. V., and T. M. Lillesand. 1992. Improved classification of forest vegetation in northern Wisconsin through a rule-based combination of soils terrain, and LANDSAT Thematic Mapper data. For. Sci. 38(1):5-20.

Brown, J. K. 1974. Handbook for inventorying downed woody fuel. USDA For. Serv. Gen. Tech. Rep. INT-16. 24 p.

Ciesla. W. M., and M. M. Furniss. 1986. Idaho's haunted forests. Am. For. 81(8):32-35.

Cheff, B. 1984. What has happened to the Montana Grizzly. Report on file at the USDA For. Serv., Intermountain Fire Sciences Lab., Missoula, Montana. 13 p.

Congalton, R. G. 1991. A review of assessing the accuracy of classifications of remotely sensed data. Remote Sensing of the Environment. 37:35-46.

Craighead, J. J., J. S. Summer, and G. B. Scaggs. 1982. A definitive system for analysis of grizzly bear habitat and other wilderness resources utilizing LANDSAT multispectral imagery and computer technology. Wildlife-Wildlands Institute Monograph No. 1, Univ. of Montana Foundation, Univ. of Montana, Missoula. 279 p.

Deiss, C. 1958. Geology of the Bob Marshall Wilderness. *In* Guide to the Bob Marshall Wilderness.

USDA For. Serv. Northern Region Rep., Missoula, Montana. 36 p.

Elvidge, C. D. 1988. Thermal infrared reflectance of dry plant materials: 2.5-20.0 micrometers. Remote Sensing of Environment. 26:265-285.

Ferner, J. W. 1974. Habitat relationships of *Tamiasciurus hudsonicus* and *Sciurus aberti* in the Rocky Mountains. Southwest Nat. 18:470-473.

Gabriel, H. W. 1976. Wilderness ecology: The Danaher Creek drainage, Bob Marshall Wilderness, Montana. Univ. Montana, Missoula. Ph.D. Dissertation. 224 p.

Gauch, H. G. 1982. Multivariate analysis in community ecology. Cambridge University Press, New York. 298 p.

Hann, W. J. 1990. Landscape ecology and vegetation management in whitebark pine ecosystems. *In* Proceedings of Whitebark pine ecosystems: Ecology and management of a high mountain resource. March 29-31, 1989, Bozeman, Montana. USDA For. Serv. Gen. Tech. Rep. INT-270.

Hann, W. J., M. E. Jensen, and R. E. Keane. 1989. Chapter 4: Ecosystem management handbook–ECODATA methods and field forms. USDA For. Serv. Northern Region Handbook. On file at USDA For., Serv., Northern Region, Missoula, Montana. 123 p.

Hill, M. O. 1979a. DECORANA–A FORTRAN program for Detrended Correspondence Analysis and reciprocal averaging. Ithaca, New York, Cornell Univ. 33 p.

________. 1979b. TWINSPAN–A FORTRAN program for arranging multivariate data in an ordered two-way table by classification of individuals and attributes. Ithaca, New York, Cornell Univ. 43 p.

Hoff, R., R. Bingham, and G. J. Macdonald. 1980. Relative blister rust resistance of white pines. European J. For. Pathology. 10:307-316.

Hoff, R. J., and G. I. Macdonald. 1977. Different susceptibility of 19 white pine species to woolly aphid (*Pineus coloradensis*). USDA For. Serv. Res. Note INT-225. 4 p.

Jensen, J. R. 1986. Introductory digital image processing–a remote sensing perspective. Prentice Hall, New Jersey. 379 p.

Joria, P. E., and S. C. Ahern. 1991. A comparison of the SPOT and LANDSAT Thematic Mapper satellite systems for detecting gypsy moth defoliation in Michigan. Photogrammetric Engineering and Remote Sensing. 57(12):1605-1612.

Keane, R. E., and S. F. Arno. 1993. Rapid decline of whitebark pine in western Montana: Evidence from 20-year remeasurements. W. J. Appl. For. 8(2):44-47.

Keane, R. E., M. E. Jensen, and W. J. Hann. 1990. ECODATA and ECOPAC–analytical tools for integrated resource management. The Compiler. 8(3):24-37.

Keane, R. E., and P. Morgan. 1994. Landscape processes affecting the decline of whitebark pine in the Bob Marshall Wilderness Complex of Montana, USA. *In* Proceedings of the 12th Symposium on Fire and Forest Meterology, Jekyll Island, Georgia, October 28-30, 1993. (In press).

Kendall, K. C. 1980. Bear-squirrel-pine nut interaction. *In* Yellowstone grizzly bear investigations. Annual Report 1978-1979. USDI Nat. Park Serv. Pp. 51-60.

Kendall, K. C. 1993. Whitebark pine management issues in national parks. *In* Proceedings of the international symposium, Subalpine Stone Pines and Their Environment. St. Moritz, Switzerland, Sept. 1992. USDA Gen. Tech. Rep. (In press).

Kendall, K. C., and S. F. Arno. 1990. Whitebark pine–an important but endangered wildlife resource. *In* Proceedings of the symposium: Whitebark pine ecosystems: Ecology and management of a high mountain resource, March 29-31, 1989, Bozeman, Montana, USA. USDA For. Serv. Gen. Tech. Rep. INT-270. Pp. 264-274.

Kenneweq, H. 1989. Remote sensing approaches to assessment and diagnosis of forest decline. *In* Air pollution and forest decline. J. B. Bucher and I. Bucher-Wallin (eds.). Proceedings, 14th Int. Meeting for specialists in air pollution effects on forest ecosystems, IUFRO P2.05, Interlaken, Switzerland, Oct. 2-8, 1988. Pp. 217-221.

Landauer, G. 1989. Detection, classification, and mapping of forest decline by means of multispectral remote sensing. *In* Proceedings of the International Conference and Workshop: Global natural resource monitoring and assessments: Preparing for the 21st century. Venice, Italy. Pp. 468-472.

Leckie, D. G., and D. P. Ostaff. 1988. Classification of airborne multispectral scanner data for mapping current defoliation caused by the spruce budworm. For. Sci. 34(2):259-275.

Leckie, D. G., P. M. Teillet, G. Gedosejevs, and D. P. Ostaff. 1988. Reflectance characteristics of cumulative defoliation of balsam fir. Can. J. For. Res. 18:1008-1016.

Leprieur, C. E., J. M. Durand, and J. L. Peyron. 1988. Influence of topography on forest reflectance using LANDSAT Thematic Mapper and digital terrain data. Photogrammetric Engineering and Remote Sensing. 54(4):491-496.

Losensky, J. 1990. A comparison of the 1988 fire season to the historical role of fire for the Bob Marshall-Great Bear-Scapegoat wilderness complex. A report on file at the USDA For. Serv., Intermountain Fire Sciences Lab., Missoula, Montana.

Mattson, D. J., B. M. Blanchard, and R. R. Knight. 1991. Food habits of Yellowstone grizzly bears, 1977-1987. Can. J. Zoology. 9:1619-1629.

Moore, M. M., and M. E. Bauer. 1990. Classification of forest vegetation in north-central Minnesota using LANDSAT multispectral scanner and Thematic Mapper data. For. Sci. 36(2):330-342.

Perry, C. R., and L. F. Lautenschlager. 1984. Functional equivalence of spectral vegetation indices. Remote Sensing of Environment. 14:169-182.

Pfister, R. D., B. L. Kovalchik, S. F. Arno, and R. C. Presby. 1977. Forest habitat types of Montana. USDA For. Serv. Gen. Tech. Rep. INT-34. 174 p.

Price, J. C. 1987. Calibration of satellite radiometers and the comparison of vegetation indices. Remote Sensing of Environment. 21:15-27.

Puritch, G. S. 1981. Nonvisual remote sensing of trees affected by stress. Can. For. Serv., Pacific For. Res. Centre, For. Tech. Rep. 30. 39 p.

Rock, B. N., and J. E. Vogelmann. 1989. The use of remote sensing for the study of forest decline. *In* Proceedings of the International Conference and Workshop: Global natural resource monitoring and assessments: Preparing for the 21st century. Venice, Italy. Pp. 468-472.

Rock, B. N., J. E. Vogelmann, D. L. Williams, A. F. Vogelmann, and T. Hoshizaki. 1986. Remote detection of forest damage. BioScience. 36(7):439-445.

Schowengerdt, R. A. 1983. Techniques for image processing and classification in remote sensing. Academic Press, New York. 289 p.

Soil Conservation Service. 1981. Average annual precipitation, Montana, based on 1941-1970 base period. USDA Soil Conservation Service, Portland, Oregon. 16 p.

Tomback, D. F. 1982. Dispersal of whitebark pine seeds by Clark's nutcracker: a mutualism hypothesis. J. of Animal Ecol. 51:451-467.

Tomback, D. F., L. A. Hoffmann, and S. K. Sund. 1990. Coevolution of whitebark pine and nutcrackers: Implications for forest regeneration. In Proceedings of Whitebark pine ecosystems: Ecology and management of a high mountain resource. March 29-31, 1989, Bozeman, Montana. USDA For. Serv. Gen. Tech. Rep. INT-270. Pp. 118-130.

USA CERL. 1990. GRASS 4.0 Reference Manual. United States Army Corps of Engineers, Construction Engineering Research Laboratory, Champaign, Illinois. 208 p.

Vogelmann, J. E., and B. N. Rock. 1986. Assessing forest decline in coniferous forests of Vermont using NS-001 Thematic Mapper Simulator data. Int. J. Remote Sensing. 7(10):1303-1321.

Received 20 June 1993
Accepted for publication 1 February 1994