Post-logging stand characteristics and crown development of whitebark pine (Pinus albicaulis)
by Todd Roger Kipfer

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Earth Sciences
Montana State University

Abstract:
Whitebark pine (Pinus albicaulis) is an important and potentially threatened high-elevation tree. In order to increase the knowledge of factors influencing whitebark pine growth characteristics for potential management strategies and actions, the competitive influence of neighboring trees on individual whitebark pine crown characteristics was assessed using a distance-dependent competition index. Approximately 300 subject whitebark pine trees and selected competing trees were measured in three study stands that were logged between 1968 and 1972. The study stands were in the Gallatin National Forest, Montana. The competition index quantified competitive pressure from the number, size, and spatial arrangement of competing trees using tree height ratios and inter-tree distances. The subject whitebark pine trees were identified according to whether or not they established before or after the logging. Those trees that established before the logging were not further evaluated. Regression analysis evaluated the relationships between the competition index, and four subject whitebark pine measures: (I) total tree height, (2) crown diameter, (3) crown diameter/total tree height, and (4) crown volume.

Significant inverse correlations between the competition index and each measure were found, but the percent variation in the measures' explained by the competition index was low. Subject whitebark pine tree ages and differences between stands were also significant factors affecting the four whitebark pine measures. Possible competition index thresholds were qualitatively identified. The results were similar to previous competition index/tree growth studies, and continued research on factors affecting whitebark pine growth characteristics was discussed.

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of

Master of Science

in

Earth Sciences

MONTANA STATE UNIVERSITY
Bozeman, Montana

July 1992

APPROVAL

of a thesis submitted by

Todd Roger Kipfer

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

July 31, 1992
Date

Katherine Hansen
Chairperson, Graduate Committee

Approved for the Major Department

8/3/92
Date

D.K. Lay
Head, Major Department

Approved for the College of Graduate Studies

8/6/92
Date

R L Brown
Graduate Dean

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ACKNOWLEDGMENTS

Funding for this study was provided by the Department of Earth Sciences, the Center for High-Elevation Studies, and the Forestry Sciences Lab at Montana State University (M.S.U). Kathy Hansen, an associate professor of geography and the director for the Center for High-Elevation Studies at M.S.U., contributed to the thesis by encouraging research in mountain environments and by editing numberless thesis drafts. Ward McCaughey, a researcher with the Intermountain Research Station's Forestry Sciences Lab at M.S.U., instigated this study and gave important technical help. William K. Wyckoff, an associate professor of geography at M.S.U., broadened my understanding of geography by teaching me about professional geography and the American West. John Wilson, an associate professor of geography at M.S.U., provided a rigorous review of this study that significantly improved the final version. Finally, Chad Kipfer, my brother, and Julie Kipfer, my wife, were dedicated field assistants.

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ABSTRACT

Whitebark pine (*Pinus albicaulis*) is an important and potentially threatened high-elevation tree. In order to increase the knowledge of factors influencing whitebark pine growth characteristics for potential management strategies and actions, the competitive influence of neighboring trees on individual whitebark pine crown characteristics was assessed using a distance-dependent competition index. Approximately 300 subject whitebark pine trees and selected competing trees were measured in three study stands that were logged between 1968 and 1972. The study stands were in the Gallatin National Forest, Montana. The competition index quantified competitive pressure from the number, size, and spatial arrangement of competing trees using tree height ratios and inter-tree distances. The subject whitebark pine trees were identified according to whether or not they established before or after the logging. Those trees that established before the logging were not further evaluated. Regression analysis evaluated the relationships between the competition index and four subject whitebark pine measures: (1) total tree height, (2) crown diameter, (3) crown diameter/total tree height, and (4) crown volume. Significant inverse correlations between the competition index and each measure were found, but the percent variation in the measures explained by the competition index was low. Subject whitebark pine tree ages and differences between stands were also significant factors affecting the four whitebark pine measures. Possible competition index thresholds were qualitatively identified. The results were similar to previous competition index/tree growth studies, and continued research on factors affecting whitebark pine growth characteristics was discussed.

CHAPTER 1

INTRODUCTION

Mid-latitude, high-elevation environments exhibit a fragile complexity and have often, in the past, been relatively inaccessible to development. Although these landscapes in much of western North America have largely remained intact (Wardle 1968), increasing anthropogenic activity is creating impacts at large, ecosystem or landscape scales (Veblen 1987). Also, societal values of these high-mountain forest resources have undergone significant changes to include recreation, watershed management, wilderness, and wildlife preservation (Ives 1990). The effects of fire suppression, exotic species introductions, landscape fragmentation, global climate change, and other society-environment interactions could have potential deleterious impacts on high-elevation ecosystems. Specific solutions will likely rely on reactive measures, focused on specific ecosystem components because many of these impacts have only recently been observed and are now only partially understood. For example, management actions may become specifically focused on the maintenance of a specific species or a specific population that is identified as threatened.

Study Objectives

This study focuses on increasing the understanding of an important and potentially threatened high-elevation tree, whitebark pine (*Pinus albicaulis*), so that this information can be used to develop improved policies and more appropriate management actions. Specifically, this study quantifies the influence of competition from neighboring trees on the crown characteristics of individual, regenerating whitebark pine trees in logged stands. The growth characteristics of individual trees depend upon numerous factors that vary spatially and temporally. However, competition is an important factor influencing tree growth that has been successfully related to tree growth characteristics for many commercially important tree species (Lorimer 1983; Tomé and Burkhart 1989).

Four objectives were identified to evaluate the relationships between competition and whitebark pine crown characteristics. The objectives are: (1) to describe the crown characteristics of regenerating whitebark pine in the study stands, (2) to statistically compare crown characteristics for two types of whitebark pine in the study stands (i.e., those trees that established before the logging and survived, referred to as advance growth trees, and those trees that established after the logging, referred to as subsequent regeneration trees), (3) to quantify and describe the amount of competition from neighboring trees on individual whitebark pine for the study stands, and (4) to evaluate the variability in whitebark pine crown characteristics explained by the competition indices.

Management Implications

Whitebark pine (*Pinus albicaulis*) is an important, but potentially endangered, high-elevation resource (Kendall and Arno 1990). It occupies subalpine forest zones and forms upper timberline in the northwestern United States and western Canada. Whitebark pine populations, however, may be declining. Arno (1986) cites increased whitebark pine mortality and links it to insect and disease epidemics and successional replacement related to fire suppression. In western Montana and northern Idaho, blister rust (*Cronartium ribicola* J.C. Fisch. ex Rabenh.) has caused 80 to 90% mortality of whitebark pine stands. Blister rust is present in the Greater Yellowstone Ecosystem (GYE) but has not caused widespread mortality, probably due to the GYE's relatively cold and dry climate (Hoff and Hagle 1990).

The predicted impacts of potential climate change on whitebark pine forests within the GYE are severe, and climate change may constitute the most serious long-term threat to whitebark pine in the region. Romme and Turner (1991) anticipate a more fragmented and reduced whitebark pine zone as a consequence of climate change in the GYE for three different scenarios of climate change. The three likely climate scenarios were: (1) warmer and drier than the present; (2) warmer and drier, but with a compensating increase in plant water use efficiency; and, (3) warmer and wetter than the present. Under climate scenario (1), available habitat for whitebark pine forests, currently occupying approximately 250,000 hectares within Yellowstone National Park and the adjacent high peaks, is predicted to decrease by 90%. A similar habitat loss is predicted for climate scenario (2). Habitat loss for whitebark pine forests is also predicted for climate scenario (3), and because whitebark pine may currently be restricted to the drier summer climates that characterize the northern Rocky Mountains, the wetter conditions under this scenario may contribute to an increased reduction in whitebark pine or even local extinction. It is believed that relatively cool and dry conditions have prevented widespread blister rust infestation in the GYE (Hoff and Hagle 1990). Warmer and wetter conditions may bring about increased blister rust infestation in the GYE, magnifying the negative impacts of climate scenario (3) for whitebark pine populations.

Whitebark pine ecosystems provide significant wildlife habitat. The large seeds produced by whitebark pine are an important and preferred high-energy food source for several wildlife species including the endangered grizzly bear (*Ursus arctos horribilis*) (Craighead et al. 1982; Kendall 1983; Kendall and Arno 1990), the red squirrel (*Tamiasciurus hudsonicus*), and the Clark's nutcracker (*Nucifraga columbiana*) (McCaughey and Schmidt 1990).

Because of whitebark pine's predicted decline and its importance for high-elevation wildlife habitats, continued seed production and survival of naturally regenerating whitebark pine are pressing concerns for ecological researchers and land managers (Eggers 1986; Hillis 1986; Weaver and Forcella 1986; Tyers 1990). McCaughey and Weaver (1990) suggested that the probability of natural regeneration of whitebark pine in wildlife-sensitive areas is likely decreasing, and future management of whitebark pine forests will require assessment and management of factors such as competition and disease. Research aimed at finding ways to manage competition and disease for enhanced whitebark pine seed production, regeneration survival, and specific growth characteristics is only just now getting started.

The effects of silvicultural management options for maintaining or enhancing whitebark pine ecosystems are not well documented (Eggers 1990; Schmidt and McCaughey 1990). Management actions that may increase seed production by increasing the proportions of the crown that are fully exposed to light include: thinning, fertilization, and protection from insects and other seed destroying agents (Eggers 1990). The effect of these actions on residual whitebark pine seedlings and saplings is not well understood. Observations by Eggers (1990) indicate that advance growth whitebark pine seedlings and saplings have responded little to release (i.e., removal of forest competition) and additional data are needed.

Quantifying the influence of competing vegetation on conifer growth can help to determine silvicultural prescriptions, optimize management decisions, and provide a basis for growth models of young forest stands (Wagner and Radosevich 1991b). Neighboring species compete for necessary resources such as light, water, and nutrients, and this competition influences the structure and composition of a forest community (Spurr and Barnes 1980). The management of interspecific competition may also influence the rate and course of development for young conifer stands (Stewart et al 1984; Walstad and Kuch 1987). Resource managers interested in maximizing crown growth characteristics and seed production can also benefit from a better understanding of the relationships between whitebark crown growth characteristics and the competitive influence of neighboring trees.

Previous Studies

Biogeography

Geographers increasingly have assessed human influences on the spatial pattern and dynamics of vegetation (Veblen 1987). Many geographers have studied the effect of disturbance, anthropogenic and natural, on vegetation patterns and processes, focusing, for example, on fire (Vale 1979; Parker and Parker 1983; Veblen 1986; Veblen and Lorenz 1986), climate (Hansen-Bristow and Ives 1984), settlement and land use (Dando and Hansen 1990; Wyckoff and Hansen 1991), avalanches (Butler 1985; Malanson and Butler 1986), and tree falls (Beatty 1984; Veblen 1985). High-elevation forests have received increasing attention by American geographers with much of the work regionally focused in the American West (Ives and Hansen-Bristow 1983; Hansen-Bristow and Ives 1984; Hansen-Bristow and Ives 1985; Veblen 1986; Baker 1988; Parker 1988; Taylor 1990). The remainder of this review focuses on those aspects pertinent to this study.

Inter-Tree Competition and Tree Growth

The effect of competition on the growth of individual trees has been studied for many species (Tomé and Burkhart 1989) but not for whitebark pine. These studies have used individual tree growth models based on competition indices to quantify the amount of competition from neighboring trees. The growth of individual trees on specific sites depends upon many factors, including past growing conditions, genetic ability to grow, micro-environment, competitive status, and influence of local neighbors (Tomé and Burkhart 1989). For studies looking at incremental growth characteristics (i.e., growth over time), past-growing conditions and genetic ability to grow are introduced in growth models by incorporating initial tree dimensions. The influence of local neighbors is accounted for by interpreting stand densities and size structures at local or stand-level scales. The majority of these studies have focused on the growth of individual, economically important trees in plantations or homogeneous stands (Daniels et. al 1986; Tomé and Burkhart 1989; Wagner and Radosevich 1991b). Other studies have used competition-tree growth models to compare the shade tolerance of tree species (Lorimer 1983), to assess reproductive strategies in mixed species forests (Woods and Whittaker 1981), and to evaluate the susceptibility of individual trees to insect attack (Ellis 1979).

Competition indices can be categorized as either distance-independent or distance-dependent (Munro 1974; Tómé and Burkhart 1989). Distance-independent indices (using a whole stand approach) have been used to predict the mean ability of the average tree or whole stand to grow based on average measures of vegetation abundance throughout the stand. Distance-dependent indices (using an individual-tree or neighborhood approach) measure the influence of local neighbors on an individual subject tree's ability to grow. Although both approaches predict with a similar precision, distance-dependent indices are expected to provide a greater precision and are considered more satisfactory than distance-independent indices (Alemdag 1978; Firbank and Watkinson 1987; Goldberg 1987; Tomé and Burkhart 1989; Wagner and Radosevich 1991a). The influence of competition on stand dynamics cannot be fully examined with whole-stand approaches because individual trees in young stands are typically surrounded by a variation of species, growth forms, ages, origins, densities, proportions, and spatial arrangements that change through time (Firbank and Watkinson 1987; Wagner and Radosevich 1991a).

Neighborhood or distance-dependent models of competition can be divided into four types (Firbank and Watkinson 1987; Wagner and Radosevich 1991a). The first type quantifies the degree of crown overlap with neighboring trees (Newnham and Smith 1964; Bella 1971; Ek and Monserud 1974; Daniels et al. 1986); the second type counts the number of neighbors (Alemdag 1978; Firbank and Watkinson 1987); the third type measures the area available to individual trees (Brown 1965; Moore et al. 1973; Jensen 1974; Pelz 1978; Watkinson et al. 1983; Mithen et al. 1984; Daniels et al.

1986); and, the fourth type combines the number, size, and distance of neighbors in a composite statistic (Hamilton 1969; Hegyi 1974; Daniels 1976; Alemdag 1978; Daniels et al. 1986; Wagner and Radosevich 1991a and 1991b). Simple competition indices that include competitor size and inter-tree distances generally perform as well as the more complex competition-growth models that assess local spatial pattern (Lorimer 1983).

Previous studies using neighborhood models to assess individual tree growth in response to competition suggest an inverse relationship between the amount of competition from neighbors and individual tree growth performance. Daniels (1976) found correlations between simple distance-diameter competition indices and total height increments ($r = -0.207$ to -0.424) and diameter at breast height (dbh) increments ($r = -0.141$ to -0.456) of Loblolly pine (*Pinus taeda* L.) in Virginia tree plantations. Daniels et al. (1986) compared competition indices for correlation with annual dbh and basal area growth of loblolly pine. The analysis used simple correlation, contribution to multiple correlation, and multiple regression analysis to evaluate the contribution of the competition index. Negative simple correlation coefficients were interpreted to represent competitive stress and ranged from -0.6316 to -0.7143 for annual dbh and from -0.3807 to -0.5574 for tree basal area. In the multiple regressions, squared multiple correlation coefficients (R^2)

between pine basal area growth and distance-dependent competition indices ranged from 0.387 to 0.686. For pine diameter growth, the multiple correlation coefficients ranged from 0.249 to 0.652.

In a similar comparative study, Tomé and Burkhart (1989) compared distance-dependent competition indices for growth prediction in *Eucalyptus globulus* plantations. They found consistently significant correlations between calculated distance-dependent competition indices and dbh and basal area growth. Simple and multiple correlations were similar to those of Daniels et al. (1986). Simple distance-diameter indices explained subject tree growth variation with a precision similar to other indices. They also modified the existing indices based on the premise that neighboring trees larger than a subject tree contributed a competitive influence, whereas neighboring trees smaller than a subject tree were competitively influenced by the subject tree. Regression analysis evaluated the competition indices as predictor variables, and they found higher correlations using the modified indices.

Lorimer (1983) modified a distance-diameter competition index for interpreting changes in the index over time. His study examined natural hardwood stands where spatial variability was much higher than would be typically found in a tree plantation. Various modified indices were utilized as predictor variables against diameter growth in bivariate regressions. The search radius used to identify competitors, the distance function used in the index computation, and the criteria used to select and evaluate competitors were varied. Significant ($p < 0.05$) coefficients of determination (R^2) ranged from 0.07 to 0.74, depending upon the geography of the stand location (i.e., Nettleton, WI, Black Rock, NY, or Prospect Hill, MA) and the tree species selected as the subject species.

Other researchers have assessed the influence of interspecific competition in young plantations. In a study of *Pseudotsuga* menziesii saplings in the Oregon Coastal range, Wagner and Radosevich (1991a, 1991b) found significant relationships between calculated interspecific competition indices and *Pseudotsuga menziesii* growth measures. Multiple regression analysis used nine independent variables against four dependent variables. The independent variables included subject tree age, a competition index, the height of the tree after the first growing season after planting, slope, and slope azimuth. Dependent variables included total height, stem diameter, a stem volume index, and a crown volume index. Tree age accounted for between 34 and 42% of the variation in tree size. A competition index summing the percent cover for all woody species that were equal to or taller than the subject tree in a 2.1 meter radius neighborhood was the best predictor of *Pseudotsuga menziesii* height growth.

The effects of inter-tree competition on the morphological growth performance of individual whitebark pine trees has not been well documented. Previous studies have assessed whitebark pine incremental growth and stand dynamics. Peterson et al. (1990) used dendrochronological methods to assess long-term growth trends of whitebark pine in response to climatic and other environmental variables in the Sierra Nevada range. Weaver et al. (1990) studied successional patterns in 47 stands containing whitebark pine (*Pinus albicaulis*-*Vaccinium* scoparium habitat type (following Pfister et al. 1977) in Montana, Wyoming, and Idaho. Competition was assessed in terms of stand development rather than individual tree growth characteristics. One important result of their research applied to the gap size needed for seedlings to grow into saplings. Although the density of seedlings remained approximately constant across stands of different ages it was hypothesized that growth from seedling to sapling size could not be supported in stands older than 100 years. They suggested that clearings needed to be larger than 10 m^2 for seedlings to grow into saplings.

Geography and Ecology of Whitebark Pine

Analysis of the influence of competition on the crown characteristics of whitebark pine requires an assessment of the general geography and ecology of whitebark pine. From seed dispersal to geographic distribution, this high-elevation tree exhibits specialized characteristics that warrant attention for understanding crown characteristics and local stand factors.

The geography of whitebark pine extends from northern British Columbia to central California and west from the Pacific coastal ranges to the northern and coastal Rocky Mountains (Figure 1) (Arno and Hoff 1989; McCaughey and Schmidt 1990). Whitebark pine occupies an altitudinal range of 1520 to 3050 m (5000 - 10,000 ft) in Idaho and Montana (McCaughey and Schmidt 1990). Other available data on site characteristics of whitebark pine stands in the GYE show a wide range of elevations, slopes, and aspects (Hansen-Bristow et al. 1990). For example, whitebark pine stands occur at an altitudinal range of 2075 meters to 2895 m (6180 - 9500 ft) and slopes of 0% to 45% in a wide range of aspects in the Gallatin National Forest, Montana. In contrast, elevations ranged from 2400 m to 3050 m (7,710 - 10,000 ft) on slopes ranging from 5% to 90% in the Bridger-Teton National Forest, Wyoming. The trees here have a preference for south and west aspects.

The high-mountain landscapes which whitebark pine occupy are harsh areas characterized by instability (Hansen-Bristow et al. 1990). At its upper elevational limits, the harsh climatic conditions include extreme winter temperatures of -51°C (-60°F) and summer temperatures exceeding 38°C

(100°F) (McCaughey and Schmidt 1990). Strong winds and snowfall add to the harsh conditions. The soils of whitebark pine are typically thin and poorly developed and vary according to the parent bedrock (Hansen-Bristow et al 1990).

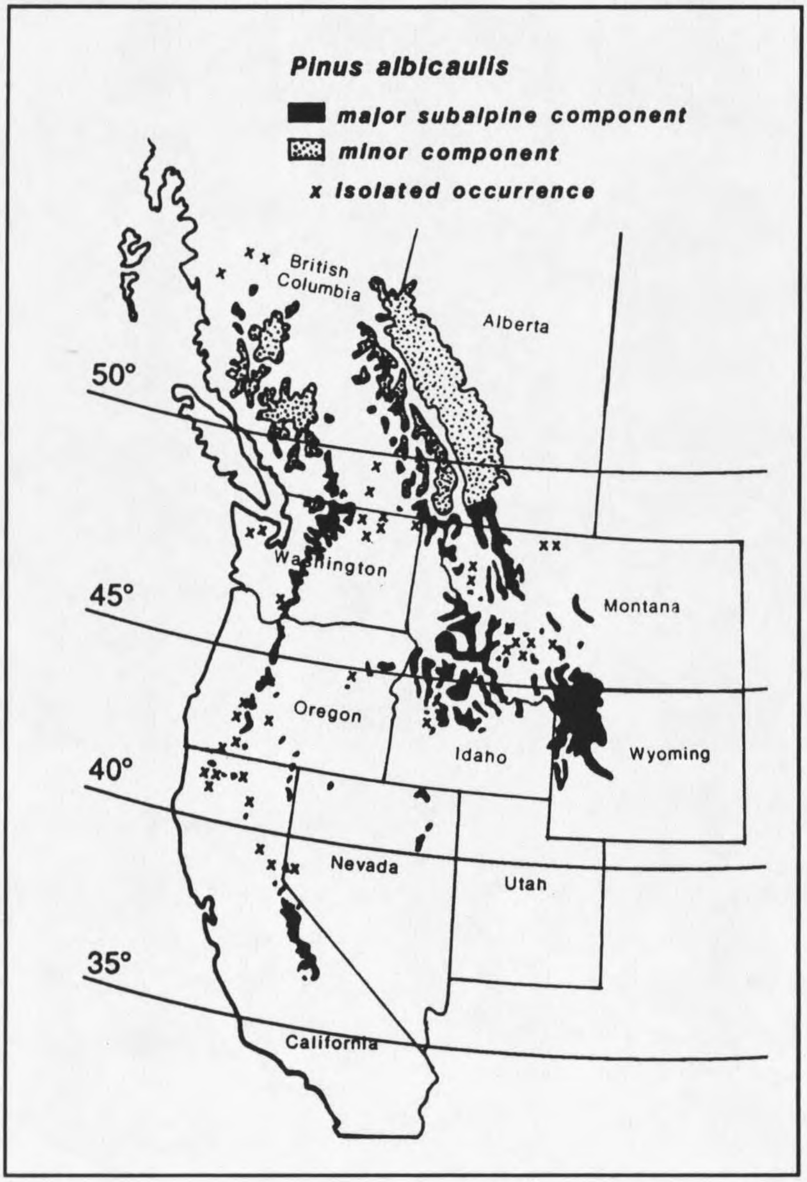

Figure 1. Geography of Pinus albicaulis in western North America (from Arno and Hoff 1989).

Needles of the pine are typically 3.8 to 6.4 cm (1.5 to 2.5 in) long and are in fascicles of five. The bark is thin, smooth, and white-gray on young stems and branches. It is about 1.3 cm (0.5 in) thick and broken into brown-white, plate-like scales with a red-brown inner bark on old trunks. The cones of whitebark pine are short-stalked and 3.8 to 7.6 cm (1.5 to 3.0 in) long (Preston 1968). The cones rapidly disintegrate from decay and depredation by animals when they reach the ground surface (Arno and Hoff 1989). The seeds are large (0.75 cm long) and wingless with a dark brown hard and thick shell (McCaughey and Schmidt 1990). Whitebark pine is extremely difficult to distinguish from limber pine (*Pinus flexilis*) when cones are not available. Identification of the number and position of resin canals of the needles (Ericson 1964) is the most effective method for differentiation of whitebark pine and limber pine in the field when cones are not available. Hendrickson and Lotan (1971), however, found Ericson's method to be unsatisfactory.

Whitebark pine typically shows a well-spread crown when grown in the open and an "upswept" upper crown similar to that of lodgepole pine in dense stands (McCaughey and Schmidt 1990). Near timberline, whitebark pine shows a prostrate form often called "krummholz." Whitebark pine is noted for multiple stems (also multi-trunked or multiple trunks) resulting from either basal branching or seed caching (Weaver and Jacobs 1990). Electrophoretic analysis revealed that two or more of the trunks of multiple stemmed *Pinus flexilis* and *Pinus albicaulis* trees were genetically distinct individuals in 20 of the 25 multi-trunk trees sampled (Linhart and Tomback 1985). The occurrence of multiple stems in whitebark pine has been shown in 8 to 79% of the trees in a study in Montana and Wyoming, and the occurrence of multiple stems decreased from open woodlands to almost zero in closed forests (Weaver and Jacobs 1990).

Reproduction in whitebark pine is heavily dependent upon the Clark's nutcracker (*Nucifraga columbiana*) and red squirrel (*Tamiasciurus hudsonicus*) for seed dissemination (McCaughey and Schmidt 1990). Predators harvest most or all seeds in some areas. Clark's nutcrackers and red squirrels harvest seeds and store them in caches, disseminating the seeds. The Clark's nutcracker may harvest and store as many as three to five times more seeds than it needs. Hutchins (1990) found that Clark's nutcracker caching is responsible for nearly all whitebark pine regeneration. Clark's nutcrackers have been observed caching whitebark pine seeds as far as 22 km from the seed source, thus effectively dispersing whitebark pine seeds to both disturbed and understory sites (Tomback et al. 1990).

Seed production is variable with poor seed crops and bumper crop years (Arno and Hoff 1989). Seed germination is highly variable (0 to 75%), and it is unknown how long the seeds remain viable in cached situations, although seeds have been observed to germinate after 2 years (McCaughey and Schmidt 1990). Weaver and Forcella (1986) evaluated cone production in whitebark pine forests, and found that stand size and canopy cover explained 52% of the variation in cone production. They hypothesized that average cone production of a stand is primarily determined by the number of fertile shoots per hectare and their interaction with weather conditions.

Whitebark pine is considered relatively competition- and shade-intolerant (Table 1) (Arno and Weaver 1990), although the trees may become more shade-tolerant with increasing age (McCaughey and Schmidt 1990). Because of its relatively low ability to compete, whitebark pine is restricted to harsh sites where more competitive trees are restricted or to less harsh sites where competition has been reduced by disturbance (Arno and Weaver 1990). Thus, disturbance is an important factor in the regeneration of whitebark pine.

Whitebark pine is frequently found growing with other high-elevation conifers, although it does form pure stands in relatively dry mountain ranges (Arno 1989). In mixed species stands, whitebark pine can form a long-lived seral co-dominant, eventually becoming replaced by the more shade tolerant species. In southwestern Montana, whitebark pine forms stands with lodgepole pine, subalpine fir, Douglas fir, and Engelmann spruce.

Table 1. Comparative tolerance of shade or competition for species associated with whitebark pine in the inland northwest. (From Arno and Weaver 1990)

Tolerance	Common name (species)
Very tolerant	Subalpine fir (*Abies lasiocarpa*) Mountain hemlock (*Tsuga mertensiana)*
Tolerant	Engelmann spruce (*Picea engelmannii*)
Intermediate or intolerant	**Whitebark pine** (*Pinus albicaulis*)
Very intolerant	Lodgepole pine (*Pinus contorta* var.latifolia) Alpine larch (*Larix lyallii*)

Pfister et al. (1977) classified forest habitat types of Montana using a modified version of Daubenmire's (1952) classification approach. This classification identifies habitat types by the potential climax tree species. Variations of each habitat type are subcategorized by the dominant understory species and called phases. Whitebark pine occurs in numerous habitat types and phases, existing as either an accidental, a minor seral species, a minor climax species, a major seral species, or a major climax species. In Montana, whitebark pine occurs as a major seral or climax species in the following habitat types: *Abies lasiocarpa* (ABLA), *Pinus albicaulis-Abies lasiocarpa* (PIAL-ABLA), *Larix lyallii-Abies lasiocarpa* (LALY-ABLA), and *Pinus albicaulis* (PIAL). Arno and Weaver (1990) summarize the landscape patterns of whitebark pine community types.

CHAPTER 2

METHODS

Study Area

Site Selection

Three logged stands in the Gallatin National Forest in Montana were sampled (Figure 2). The three stands were clear-cut logged between 1968 and 1972. The first two stands (hereafter individually identified as TEEPEE 01 and TEEPEE 02) were located in the Little Teepee Creek drainage on the southeastern edge of the Madison Range, approximately 2 km (3.2 mi) east of northwestern Yellowstone National Park and 7 km (4.4 mi) north-northeast of the Grayling Arm of Hebgen Lake. The final Moose Creek stand (MOOSE CR.) was located on the drainage divide between the Moose Creek drainage and the Swan Creek drainage that form the western slopes of the Gallatin Range, approximately 55 km (34 mi) north of the Teepee Creek stands and 17 km to the northeast of Big Sky, Montana. Sampling on the Moose Creek stand was not as

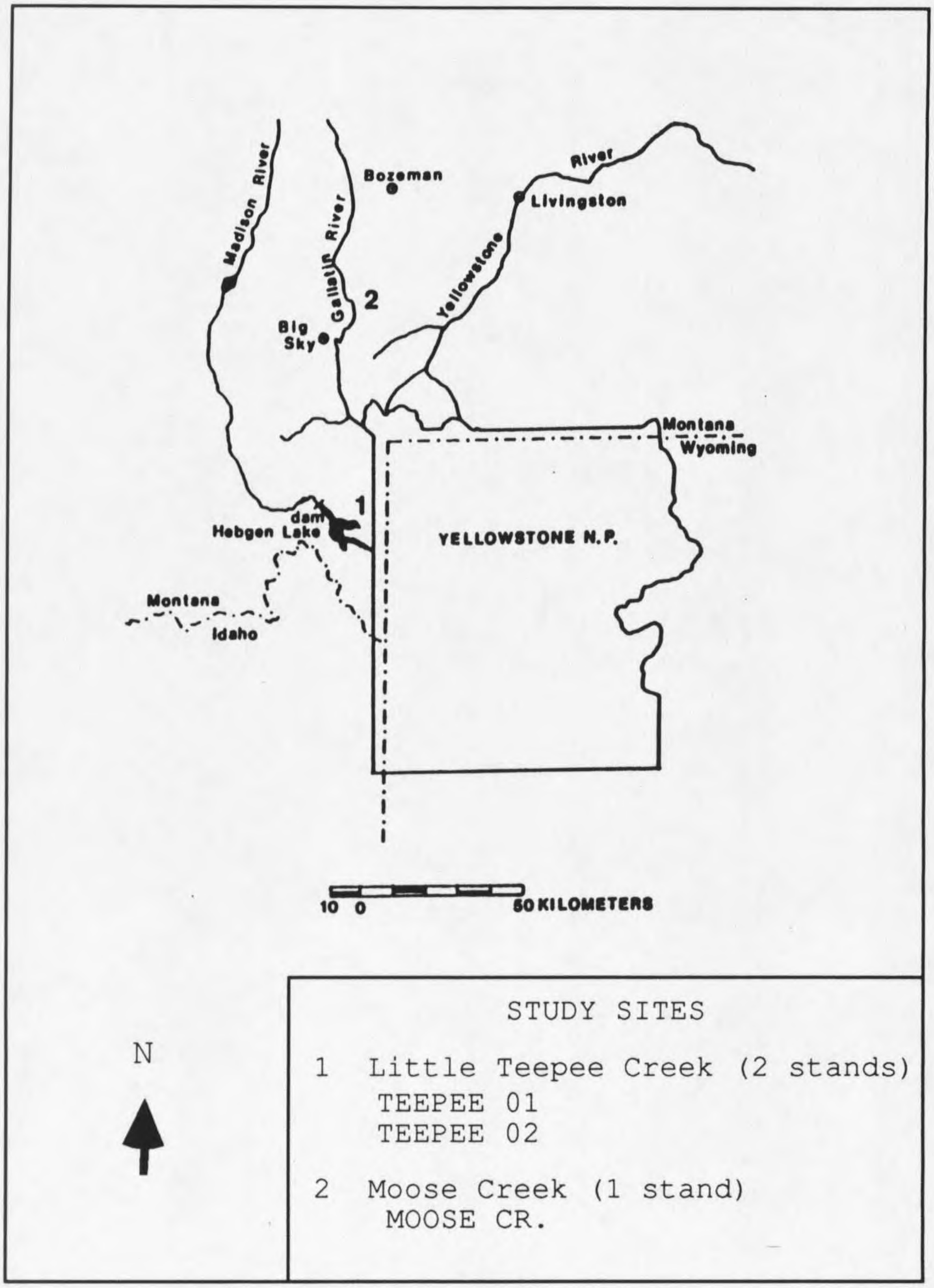

Figure 2. Map of the Yellowstone region showing the location of the two study areas that contain the three study stands.

extensive as on the two Teepee Creek stands due to the small number of whitebark pine trees in the stand. Table 2 lists general stand characteristics for the three study stands.

Table 2. General characteristics of the three study stands.

Stand	Elevation (m)	Aspect	Area (ha)	Year logged
TEEPEE 01	2450-2500	NW-NE	75	1968
TEEPEE 02	2500-2570	NE-SE	49	1970
MOOSE CR.	2130-2400	S-W	96	1972

These logged stands were selected through consultation with USDA Forest Service personnel, a USDA Forest Service database search, and individual site reconnaissance of numerous logged stands in the Gallatin National Forest. From a USDA Forest Service database search, logged stands above 1829 m (6000 ft) in the Gallatin National Forest were identified. These higher elevation, logged stands were considered to have the highest probability of containing whitebark pine. Many stands were eliminated due to difficulty with access and recent silvicultural thinning.

Criteria for selecting sites included stands logged over 15 years ago that contained whitebark pine trees. Stands with fewer than approximately 200 whitebark pine trees were considered to have too few whitebark pine for data collection needs and rejected. Once the potential sites were located, simple transects were delineated through the stands, and all observable whitebark pine trees were counted. This count produced a crude estimate of the number of whitebark pine in a stand. In the absence of cones, identification of whitebark pine in young stands was extremely difficult due to its similarity with limber pine (*Pinus flexilis*), and cross sections of fascicles were evaluated for the number and position of resin canals of the needles following Ericson (1964). Although this field method has been shown to yield errors between 44 and 47% of the time (Hendrickson and Lotan 1971), stands above approximately 2135 m (7000 ft) with a majority of field identifiable whitebark pine, determined by Ericson's method, were assumed to contain all whitebark pine.

Site Descriptions

Lodgepole pine (*Pinus contorta* var. latifolia) is the dominant tree species in all three stands. Subalpine fir (*Abies lasiocarpa*) is the second most numerous species in both of the two Teepee Creek stands, but in the lower elevation Moose Creek stand, Douglas-fir (*Pseudotsuga menziesii*) is the second most numerous species, reflecting a different habitat type. The number of whitebark pine varies in the three stands, with the largest number in the highest elevation Teepee Creek stand (TEEPEE 02) and the smallest number in the relatively lower elevation Moose Creek stand. Engelmann spruce (*Picea engelmannii*) is a minor component of the two Teepee Creek stands, occupying more north facing aspects, and was not found in the Moose Creek stand. Juniper (*Juniperus* spp.) is prevalent in the Moose Creek stand but rare in the relatively higher elevation Teepee Creek stands.

The understory of the logged stands varies, but Grouse Whortleberry (*Vaccinium scoparium*) was common with a conspicuous component of fire weed (*Epilobium* spp.). Grasses dominate the more open portions of the stands and are more common in the Moose Creek stand. Burned slash remnants from logging are very common in all three stands.

The Moose Creek stand is probably a different habitat type (Pfister et al. 1977) than the two Teepee Creek stands. Although not directly sampled, observations suggest that the two Teepee Creek stands are in an early phase of the *Abies lasiocarpa /Vaccinium scoparium* (ABLA/VASC) habitat type. The Moose Creek stand was not classified, but it is noticeably different from the two Teepee creek stands due to the presence of *Pseudotsuga menziesii* and the absence of *Abies lasiocarpa*.

Observed wildlife in the three stands included moose (*Alces alces*), coyote (*Canis latrans*), Clark's nutcracker, mule deer (*Odocoileus hemionus*), and small rodents (predominantly *Citellus* spp.). Throughout the Teepee Creek stands was numerous scat from bears (*Ursus* spp). Many bear scat contained a component of whitebark pine seeds.

Climatological information was obtained for the nearest climate stations. The Big Sky 3S climate station is located approximately 22 km (13.7 mi) to the southwest of the Moose Creek stand at an elevation of 2012 m (6600 ft). The Hebgen Dam climate station is located approximately 14 km (8.7 mi) to the west of the two Teepee Creek stands at an elevation of 2004 m (6489 ft). In general, both study areas are high-elevation sites characterized by extreme diurnal and seasonal climatic variability (Table 3).

Table 3. Mean annual precipitation and temperature for two climate stations nearby to the study stands.

Station	Mean annual precipitation cm (in)	Mean annual temperature °C (°F)
Big Sky 3S	44.63 (17.57)	3.39 (38.1)
Hebgen Dam	56.34 (22.18)	2.67 (36.8)

The only available soils information for the study areas was gleaned from a general soils map of Montana (US Department of Agriculture 1982). The soils of the Teepee Creek study stands can be generally characterized as mollisols-inceptisols-alfisols on gently sloping to very steep mountain slopes. The soils of the Moose Creek stand can be generally characterized as inceptisols-alfisols on gently sloping to very steep mountain slopes.

Data Collection

Data collection focused upon specific measures for selected whitebark pine trees, neighboring trees, and related factors such as understory grasses, forbs, and shrubs. The subject whitebark pine trees were identified by a systematic-random-systematic sampling procedure, using systematic transects with the distance to the initial points chosen randomly on each transect and 50 m spacing used for subsequent points. The transects were oriented north-south. For each point, the nearest whitebark pine tree greater than 0.5 m tall was selected. This method allowed for the selection of approximately 100 subject whitebark pine trees per stand.

For each subject whitebark pine tree, nested, fixed radius circular plots identified competitors. Previous studies have preferred a fixed angle gauge sweep centered at the subject tree to identify competitors (Tomé and Burkhart 1989). Simply, this method requires that with increasing distance from the subject tree, neighboring trees need to be larger in order to be selected. The application of this method was not possible for this study because of the relatively small tree sizes in the young study stands. However, three nested circular plots, each with specific tree size criteria for competitors, were utilized in order to approximate a fixed angle gauge sweep. This approach required that trees farther away from the subject tree be larger in order to be considered a competitor, such that:

(1) All tree seedlings and saplings were identified as competitors within 3.0 m radius plots centered at each

subject whitebark pine (seedlings were considered to be those trees less than or equal to 1.4 m in total tree height, and saplings were considered to be those trees greater than 1.4 m in total tree height but having a diameter-at-breast-height (dbh) less than 4.0 cm); (2) All trees with dbh greater than or equal to 4.0 cm and less than 10.0 cm were identified as competitors within the 6.0 m radius plots centered at each subject whitebark pine, and (3) All trees with dbh greater than or equal to 10.0 cm were identified as competitors within 9.0 m radius plots centered at each subject whitebark pine.

Specific measurements of the subject whitebark pine and the competing trees were selected as those considered best to calculate crown characteristics and distance-dependent competition. The whitebark pine growth characteristics evaluated by this study focused on measures of crown shape and size. Crown structure is an important factor in the productivity of forest stands. Crown structure, tree density, and the spatial distribution of trees contribute to the canopy structure, which affects stand productivity through control of within-stand light conditions (Kellomäki et al. 1985; Hashimoto 1990). Crown structure also influences seed production. Trees with narrow and suppressed crowns yield fewer seeds than open-grown trees or large dominant trees in closed forest stands with crowns well exposed to sunlight (Spurr and Barnes 1980). Crown form and horizontal canopy closure in the development of even-aged stands is often assumed to be invariant, but crown form does change because of mechanical and ecological factors as a tree grows (Zeide 1991). Trees grown in open conditions typically have full vigorous crowns that extend to or near the ground, while trees in dense stands tend to show small, narrow crowns with long cylindrical boles often without branches (Honer 1972).

Overall, five attributes were measured for each subject whitebark pine tree (Figure 3): (1) Tree age (AGE), (2) total tree height (H), (3) diameter-at-breast-height (DBH), (4) average live crown diameter (CD), and (5) height of the maximum crown diameter above the ground surface (CH). Tree age for each subject tree was determined by counting annual rings from tree cores taken by an increment borer or bole cross-sections from trees too small to core. Cores and cross-sections were taken as close to the ground surface as possible. The average live crown diameter (CD) was calculated from two perpendicular measurements taken at the widest portion of the crown.

Two crown measures were created from the measured crown characteristics. A ratio of the crown diameter to total tree height (CD/H) was used to evaluate the shape of the crown. This ratio represents how full or wide the crown is in relation to a tree's total height. Higher values of this ratio reflect trees with more horizontal crown growth