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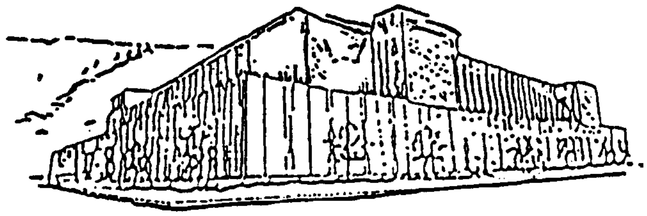

OLD-GROWTH PONDEROSA PINE IN THE BULL MOUNTAINS OF CENTRAL MONTANA

by

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BA, The Pennsylvania State University, 1993
BS, The Pennsylvania State University, 1997

Presented in partial fulfillment of the requirements
for the degree of

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Old-Growth Ponderosa Pine in the Bull Mountains of Central Montana

Directors: Carl Fiedler and Alan McQuillan

Abstract

Five randomly selected old-growth ponderosa pine (*Pinus ponderosa* var. *scopulorum*) sites on state-owned land in Musselshell County, Montana were examined for a variety of structural, temporal, and spatial attributes. Results showed that ponderosa pine was the climax species at these sites, and that old growth occurred as a component of uneven-aged forested areas on various slopes and aspects, often along drainage features. Stand densities ranged from 99 tpa to 166 tpa, and 71 ft^2/ac to 99 ft^2/ac of basal area. Regeneration was sporadic, ranging from 4 to 2056 seedlings (< 4.5 ft in height) per acre and 54 to 656 saplings (0.1 to 4.9 in dbh) per acre. Each old-growth site also contained 1.6 to 3.2 snags per acre ≥ 15.0 in. Across all five sites, 94% of sampled live trees ≥ 15.0 in were ≥ 120 years at breast height, while 17% were ≥ 300 years. Only 2 of 393 trees sampled for age were > 400 years old at breast height. Between 56% and 88% of trees ≥ 15.0 in at each site displayed crown deformities, and 14% to 43% showed evidence of fire scars. Average decadal radial increments over the past 120 years were 0.189 in for trees < 5.0 in, 0.348 in for trees 10.0 to 14.9 in, and 0.326 in for trees ≥ 15.0 in. A hypothesized decrease in tree growth since European settlement of the Bull Mountains in the early 1880's could not be verified. Several spatial statistics provided evidence of clustered large (dbh ≥ 15.0 in) tree dispersion patterns at four of the five sites and uniformly distributed large trees at one site. The five sites sampled supported uneven-aged stands maintained by relatively minor disturbances, including low intensity surface fires. This old-growth study was the first of its kind for ponderosa pine in central Montana, and should aid managers and future researchers in identifying and maintaining old growth in the region.

Acknowledgements

I would like to thank the many people whose contributions made completion of this thesis possible. First among these was Bob Wheeler, whose initial curiosity in eastside old growth provided the seed from which this project grew. Committee co-chairs Carl Fiedler and Alan McQuillan made learning at UM possible and productive by providing both research and teaching opportunities and by sharing their time and experience. Carol Brewer, from DBS, made this task both interesting and rewarding by challenging me to go further. Chris Woodall helped in a million and one ways, from being my first and most esteemed friend in Montana to assisting with fieldwork and sharing his good humor and advice throughout. DNRC foresters Brian Robbins and Don Kendall, at the Southern Land Office, and Scott McLeod and Tom Schultz, at Spurgin Road, assisted by sharing expertise in the field, providing a reliable rig, and inviting me to present at Spring Training. Scott Mincemoyer, at the USFS Fire Lab in Missoula, made the dendro work possible by providing access to a tree-ring reader.

Above all others though, I wish to thank Marnie, my patient and loving wife. She provided the physical and emotional support that carried me through this project and that makes each day not just bearable but beautiful.

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Introduction

Throughout the past two decades, definitions and values of old-growth forests have been hotly debated within the scientific community as well as in society at large (Society of American Foresters 1984, Spies and Franklin 1988, Hunter 1989, Oliver and Larson 1996, Hunter and White 1997). The arguments have evolved from questions of old growth's existence to current discussions of how to define, delineate, and manage old growth to assure the continued existence of this resource and its associated values (Burgman 1996, Rusterholz 1996, Woodgate *et al.* 1996, Shinneman and Baker 1997).

Traditionally, management of State of Montana forestland focused on revenue (timber) production for the school trust (Montana Department of Natural Resources and Conservation 1996). Montana now seeks to emphasize sustainable production while maintaining healthy and biologically diverse forests (Montana Department of Natural Resources and Conservation 1996). From an ecological perspective, old-growth forests are considered significant because of their structural diversity, slow changes in composition and structure, and complex ecological relationships (Woodgate *et al.* 1996). Accordingly, the Montana Department of Natural Resources and Conservation (DNRC) is seeking "to maintain or restore old-growth forest in amounts of at least half the average proportion that would be expected to occur with natural processes on similar sites" (Montana Department of Natural Resources and Conservation 1996).

Because of the diversity of ecological attributes associated with different forest types, it is not useful, and potentially misleading, to create a universal definition of old-growth (Hunter 1989, Burgman 1996). Burgman (1996) states that "each forest type will likely have a set of characteristics that uniquely defines old-growth forests within it and may serve to distinguish old-growth forests from other ecological assemblages, forest types, or successional stages." Among federal agencies (Forest Service, Bureau of Land Management, and National Park Service) old-growth definitions and delineation procedures have been determined at the regional or unit level and typically vary by geographic region and forest/cover type (Mehl 1992, Green *et al.* 1992, Tyrrell 1992, Beardsley and Warbington 1996, Batista and Platt 1997, Greenberg *et al.* 1997).

Several authors have echoed the need for ecologically sound thresholds in old-growth definition and delineation (Duchesne 1994, Burgman 1996, Woodgate *et al.* 1996, Hunter and White 1997). Duchesne (1994) lists 12 "required" measures for formulation of ecosystem-based ecological definitions of old growth. These measures include vertical and horizontal structures, presence and absence of regeneration, understory competition, timber volumes, age of oldest trees, dead biomass as snags or logs, topographical location, edaphic conditions, disturbance history, level of anthropogenic disturbance, floral composition and ecological land classes, and faunal components (Duchesne 1994). Woodgate *et al.* (1996) note that definitions of old-growth ought to be based upon forest growth stage, ecological vegetation classes, and evidence or modeled probability of disturbance, adding that descriptions of old-growth are "snapshots in time" resulting from dynamic and cyclic properties which cause the distribution of old growth to change.

Two general approaches for defining old growth are commonly used--structural and process. Old-growth forests typically are assumed to contain many of the following structural features: a relatively large number of large diameter trees, coarse woody debris (fallen logs), decadence, and many standing dead trees (Oliver and Larson 1996, Woodgate *et al.* 1996). The structural approach can readily be employed in the field to identify and quantify old-growth forest stands, if specific old-growth structural parameters are defined. Thus most government documents defining old growth provide lists of structural features and expected quantities of these features.

Process approaches depend primarily upon stand disturbance history and age (Moir 1992) because age alone is not adequate to define a stand as old growth. The length of time required for initiation old-growth processes is a function of site and climate factors as well as the plant community. Burgman (1996) notes that ecologically sound definitions of old growth must take into account spatial and temporal scales and severity of disturbance. Woodgate *et al.* (1996) list four classes of characteristics which provide measures of old-growth forest status. These characteristics include: 1) structural and functional attributes which are measurable and directly contribute to the description of old growth, 2) contextual attributes which are partially measurable and partially a function of human perceptions, 3) intangible attributes which are difficult to measure and largely a function of human perception, and 4) disturbance influences which may diminish or detract from the old-growth state (Woodgate *et al.* 1996). Clearly, ecologically sound definitions must include not only current structural attributes and ages, but also regional climate and disturbance histories that describe the spatial and temporal context of past and current old growth.

Montana DNRC decided upon a generic, age-based definition that considers some structural features, recognizing that "clear {ecological} thresholds beyond which a stand is, or is not, old growth do not exist" (Hunter and White 1997). For the DNRC, "Old growth is defined as stands that are 150 years and older and that exhibit a range of structural attributes associated with old age, and contain a minimum of 4000 board feet per acre, net" (McLeod 1998, Schultz 1999). This definition was to be supplemented with an "index of old-growthness" (Spies and Franklin 1988) to substantiate the definition from an ecological perspective (McLeod 1998). Inventories and methods of quantifying old-growth attributes are currently being refined by DNRC foresters (McLeod 1999). Still, little is known about the structure of, and processes affecting, Montana's old-growth ponderosa pine (*Pinus ponderosa* var. *scopulorum*) forests east of the Continental Divide.

The purpose of this thesis was to fill the gap in knowledge that managers and researchers have of ecological, temporal, growth, and spatial characteristics of old-growth ponderosa pine on Montana DNRC lands in the Bull Mountains of

Musselshell County, Montana. The methods can serve as a reference for future old-growth studies and inventories in the region, while the results provide needed information about the resource.

Specific objectives of this study were to provide background ecological information about ponderosa pine in central Montana, and to describe and quantify site, stand, and individual tree features of old-growth ponderosa pine at five sites in the Bull Mountains. This was accomplished by:

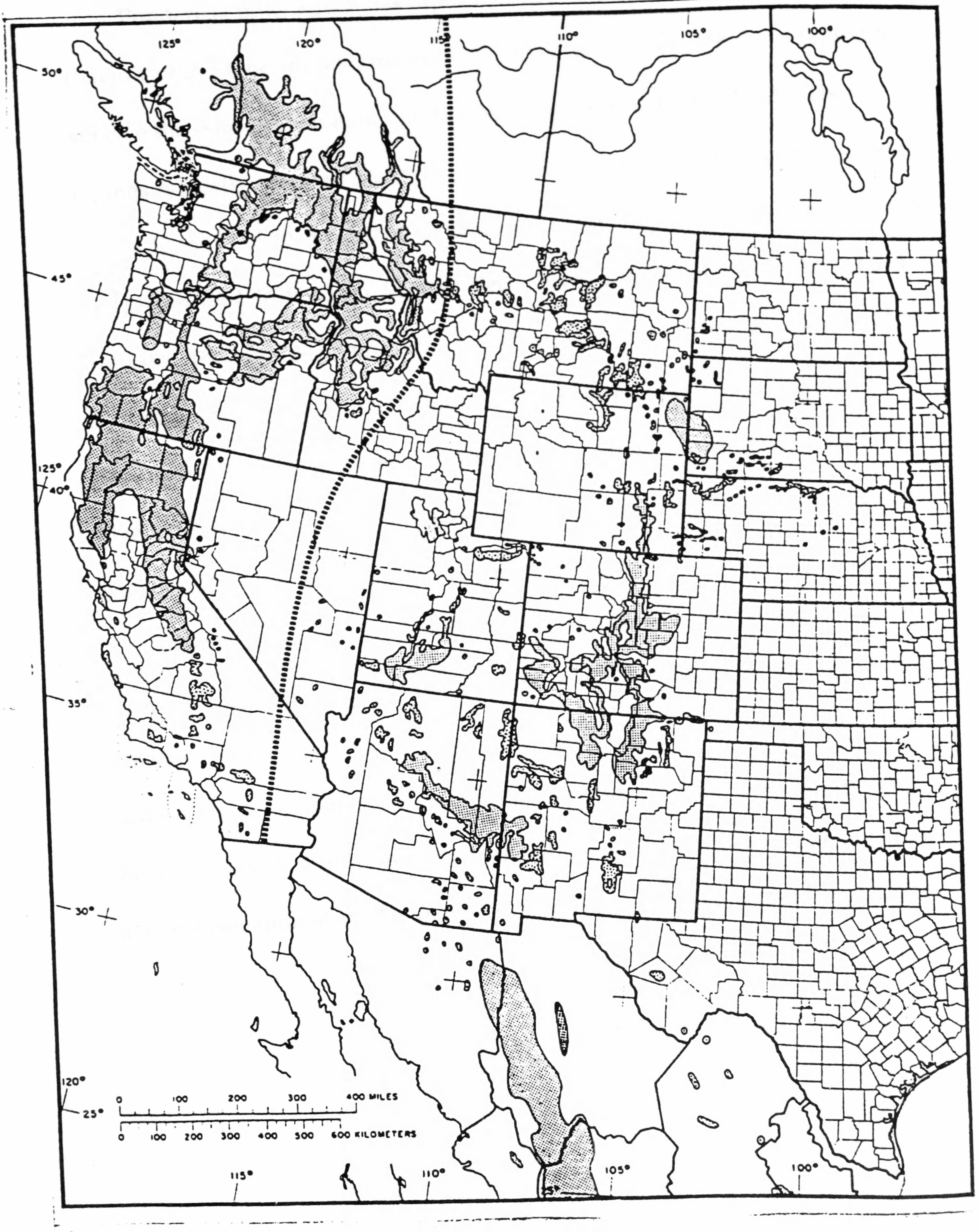
1. Reviewing literature relevant to the ecology of ponderosa pine in central Montana and old-growth ponderosa pine in other regions.
2. Describing site conditions, including: topography (slope, aspect, elevation), climate, land use, and disturbance history of the five sites.
3. Quantifying current stand conditions, including: trees per acre, basal area per acre, snags per acre, coarse woody debris, regeneration, and decadence.
4. Describing individual tree conditions, including: age and longevity, size, vigor, damage, and decadence.
5. Comparing past and current radial and basal area growth rates of Bull Mountains ponderosa pine.
6. Analyzing patterns of spatial arrangement of the large, old trees relative to the areas of land on which they occur.

Literature Review

Studies of old-growth ponderosa pine in central Montana have not previously been published. However, general ecological information is available for the species in the northern Great Plains region, which is the northeast and lower altitudinal extent of ponderosa pine's range (Oliver and Ryker 1990, Van Hooser and Keegan 1988, Green *et al.* 1985, Little 1971).

Rocky Mountain ponderosa pine (var. *scopulorum*) is found east of the Continental Divide to western North Dakota and central Nebraska (Figure 1), with more than 1.2 million acres in the Black Hills of South Dakota (Little 1971, Van Hooser and Keegan 1988, Harlow *et al.* 1991). Variety *scopulorum* has a "bushy-tuft" appearance and a greater proportion of two-needle fascicles, especially on younger trees and sites with harsh climates and less-favorable growing conditions (Conkle and Critchfield, 1988). In central and eastern Montana, where ponderosa pine is the climax tree species, Rocky Mountain juniper (*Juniperus scopulorum*) is the only other successfully reproducing tree species (Pfister *et al.* 1977). Two general groups of ponderosa pine habitat types are abundant: a shrubby group that occurs on deep, fertile soils, and a grassy group which occurs on stony or shallow soils (Pfister *et al.* 1977).

Figure 1:
Ponderosa Pine Distribution Map (from Steele 1988). Dotted line separates variety *scopulorum* (right) from variety *ponderosa* (left).



Climate, Topography, and Soils

Ponderosa pine, which has rapid root growth and vigorous taproots (Larson 1963, Stone and Jenkinson 1970, Oliver and Ryker 1990), is adapted to survive the semi-arid climatic conditions associated with grasslands. These regions typically receive 12 to 20 in (30 to 50 cm) of precipitation annually, with 5 in to 12 in (12 to 30 cm) falling as rain during the May-to-August period (Potter and Green 1964, Wells 1965, Hadley 1969, Oliver and Ryker 1990). As Table 1 indicates, the average annual total precipitation for Roundup, Montana is 12.27 in, with an average of 7.11 in falling as rain between May 1 and August 31 (McCurdy 1998). Average annual temperatures in the Great Plains range from 40 to 50°F (5-10°C), with hot, dry summers and long, windy, and cold winters (Potter and Green 1964, Oliver and Ryker 1990).

Interior ponderosa pine grows best at elevations between 4000 and 8000 ft (1220 -2439 m) in deep, well-drained soils with relatively high moisture-holding capacity (McMurray 1988). However, these site conditions are not typical of eastern Montana (Potter and Green 1964, McMurray 1988). Van Hooser and Keegan (1988) describe ponderosa pine in eastern Montana as occurring at an average elevation of 4000 ft above sea level, ranging between 2400 and 6400 ft.

Table 1:
Monthly Climate Summary for Roundup, Montana
June 1914 to December 1997

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Ave Max Temp (°F)	35.7	40.9	48.1	60.2	70.2	78.8	88.3	87.2	75.7	63.9	47.7	38.4	61.3
Ave Min Temp (°F)	11.3	15.4	21.7	31.7	41.0	49.5	54.8	52.5	42.7	33.7	22.6	14.8	32.7
Ave Total Precip (in)	0.40	0.33	0.57	1.03	2.09	2.52	1.42	1.08	1.09	0.91	0.41	0.43	12.27
Ave Total Snowfall (in)	5.8	4.0	4.7	1.4	0.2	0.0	0.0	0.0	0.2	1.2	3.2	5.0	25.7
Ave Snow Depth (in)	1	1	0	0	0	0	0	0	0	0	0	1	0

(McCurdy 1998)

On these typically dry sites, distribution is highly correlated with available soil moisture, a function of soil texture and depth (Hadley 1969, Oliver and Ryker 1990). Potter and Green (1964) note that in North Dakota grasslands ponderosa pine stands are often located on outcroppings of soil formed from weathered sandstone or scoria. Scoria is a horizontal, red shale stratum that overlies one or more lignite coal layers which have burned, causing oxidation of the shale. The soil found supporting the trees is shallow, well-drained, and coarse, whereas soils of the surrounding grasslands are deep, less well-drained, and fine textured (Potter and Green 1964). The lower limits of ponderosa pine in Wyoming are characterized by coarse-textured, sandstone-derived soils. Water is more available in these soils than in the fine-textured, limestone-derived soils favored by grasses (Hoffman and Alexander 1976).

Northern Great Plains ponderosa pine sites include topographic features such as buttes, coulees, ridges, knolls, river canyon walls, and lowlands (Potter and Green 1964, Wells 1965, Arno 1979, McMurray 1988). Wells (1965) calls the forest stands that occur on these escarpments or abrupt breaks in topography "scarp woodlands." The associated thin, residual soils are found on steep slopes and have bedrock at or near the surface (Wells 1965). Such soils and topographic features have been observed supporting ponderosa pine in western North Dakota (Potter and Green 1964, Hadley 1969), eastern Montana (Daubenmire 1968, Pfister *et al.* 1977), and northeastern Wyoming (Wells 1965).

Potter and Green (1964) note that laboratory analysis of soils supporting ponderosa pine versus soils supporting only grasses fails to indicate distinct physical or chemical differences in the fine (< 2 mm) fraction of the soils. Their study suggests that the presence of pines on rocky topographic features is a result of soils *in situ* and physiographic factors. White *et al.* (1969) conclude that soils in ponderosa pine forests of the Black Hills have horizon differentiation that is more characteristic of forest soils than of grassland soils. Soils in the adjacent grasslands appear to have been suitable for forest in the past and are thought not to be a factor causing the current prairies (White *et al.* 1969).

Ponderosa pine roots are able to exploit the water resources held in the vertical and horizontal cracks of the rocks and scoria, penetrating to depths greater than 26 ft (Potter and Green 1964). Typically, taproots can extend 6.5 ft deep in porous soils but rarely over 3.2 ft in deep in clay soils (McMurray 1988). Walter (1968) is interpreted as stating: "In both savannas and temperate semiarid areas, grasses and trees are competing for water, and grasses tend to hold a competitive advantage on drier sites" (Yazvenko and Rapport 1997). Larson and Schubert (1969) note that ponderosa pine seedling growth is greater when grown without grasses present, and that grass roots grow faster than seedling roots. However, they also state that after six years, pines had better lateral root growth than the grasses, and that established pines can better tolerate grass competition (Larson and Schubert 1969). Arno (1984) also notes that the lower timberline park-like stands contain deep-rooted ponderosas, which grow well on dry, upland sites once trees become established.

Fire and Other Disturbances

Disturbance at several spatial and temporal scales is central to the ecology of many old-growth forests because old-growth forests are not static and random disturbances play a vital role in their development (Burgman 1996). A disturbance of significant importance throughout the range of ponderosa pine is fire. The prevailing view of pre-European, climax ponderosa pine forests is of an ecosystem in "equilibrium", where frequent low-intensity surface fires maintained open, park-like stands and promoted a dynamic balance between fire and stable, long-lasting old-growth conditions (Shinneman and Baker 1997). In the park-like stands of mature and old-growth ponderosa pine, fire is carried through the understory by abundant grasses and/or small shrubs, including juniper (*Juniperus*), bunchgrasses (*Agropyron, Festuca, Stipa, Muhlenbergia,* or *Bouteloua*), sagebrush (*Artemisia*), bitterbrush (*Purshia*), or manzanita (*Arctostaphylos*), depending on the latitude and elevation of the forest community (Steele 1988, Agee 1993).

Ponderosa pine has many features that enable it to exist, and even thrive, in fire-prone environments. In addition to the deep rooting habit, other features include thick, insulating bark on large trees, a self-pruning habit that creates a bole clear of limbs, the ability to bear cones at young ages, and an open crown structure with high foliar moisture content preventing needle and bud scorch (McMurray 1988). Clearly, ponderosa pine is well-equipped to survive in the warm, dry climates typical of the Great Plains region (Daubenmire 1968, Biswell 1972) where fires ignited by lightning and Native Americans would periodically sweep across the landscape, consuming grass and small trees.

Although ponderosa pine is a fire-adapted species, the seedlings are very susceptible to burning, and often are killed by fire (McMurray 1988). Mortality from fire is primarily a function of percent crown and bud scorch (Saveland and Bunting 1988, Harrington 1993). Site quality, age, and seasonality of fire events also influence ponderosa pine's post-fire survival. Mortality is lower on good sites with fast-growing and younger trees, whereas overmature and slow growing trees (on poorer sites) are more prone to mortality (McMurray 1988). Fires occurring at the end of growing season or during the dormant season cause less mortality than spring fires (Harrington 1993).

Indications from numerous dendrochronological studies suggest that the fire regime of ponderosa pine forests has been drastically altered by Euro-American settlement, reduced burning by Native Americans, livestock grazing, and active fire suppression (Cooper 1960, Swetnam and Dietrich 1985, Baisan and Swetnam 1990, Savage and Swetnam 1990, Everett *et al.* 1994, Arno *et al.* 1995, Swetnam and Baisan 1996). Studies by Swetnam (1990), Covington and Moore (1994), and others (see Agee 1993, and Arno *et al.* 1995) show that the historic presence of fire followed by its anthropogenic exclusion can greatly alter structures and processes within stands.

Prior to Euro-American settlement of northern Arizona in the 1860's, surface fires burned through the understories of climax ponderosa pine forests near Flagstaff with a frequency of 2 to 12 years (Cooper 1960, Biswell 1972, Covington and Sackett 1984). The subsequent increase in road and trail densities in the area and the grazing by cattle and sheep in the late 1800's reduced fuel continuity. By 1908, an active fire suppression program was in effect in the Flagstaff area. Consequently, the fire frequency in the area was substantially reduced; the density of trees increased and forest litter began to accumulate (Covington and Sackett 1984, Covington and Moore 1994).

Reductions in fine fuel loading due to livestock grazing and effective fire suppression have allowed trees to invade grasslands and led to increased stand density in portions of Arizona, Nebraska, New Mexico, Montana, North Dakota, South Dakota, Utah, and eastern Oregon and Washington (Cooper 1960, Gartner and Thompson 1972, Manaday and West 1983, McMurray 1988, Covington and Moore 1994, Everett *et al.* 1994, Arno *et al.* 1995, Yazvenko and Rapport 1997). Some grassland areas in the Black Hills that once had little or no tree growth are now forested with "dog-haired" stands of ponderosa pine (Gartner and Thompson 1972, Bock and Bock 1984).

Recently, the "nonequilibrium" view of ponderosa pine has been suggested as relevant to management and conservation of Black Hills and Wyoming ponderosa pine within its range of natural variability (Shinneman and Baker 1997). This view recognizes that the traditional equilibrium view is appropriate for dry sites in the southern Black Hills, where ponderosa pine historically grew in open stands with frequent fires. However, the nonequilibrium view also accounts for evidence of longer mean fire-return intervals, large-scale outbreaks of mountain pine beetle (*Dendroctonus ponderosae*), and stand-replacing crown fires in the northern Black Hills and parts of Wyoming prior to European settlement (Knight 1994, Raventon 1994). Mehl (1992) also notes that prior to the 1870's dense ponderosa pine stands existed in portions of the Black Hills where frequent, low-intensity fires were not common. Both climate and topography are likely responsible for variations in stand density and disturbance, and localized differences in climate and topography may necessitate maintenance of "unmanaged conditions" in historically dense regions of ponderosa pine (Shinneman and Baker 1997). Traditional equilibrium influenced management may be more appropriate in historically open and mature forests of the southern Black Hills and foot hills (Shinneman and Baker 1997).

Methods

The Bull Mountains region of Musselshell County, Montana was selected because old growth in the area had not previously been studied and tree harvest was imminent. Age and location defined the tree population of interest. Trees ≥ 120 years at breast height (pith date of 1878 or earlier) were initially considered "old" because they became established before (white, Euro-American) settlers brought cattle and sheep to the Bull Mountains in the early 1880's (Musselshell Valley Historical Museum 1974, Musselshell Valley Pioneer Club 1974).

Identification of the study population was conducted indirectly because it was not possible to age all of the trees in the study region. Preliminary data collected in 1996 from three sites in the Bull Mountains revealed tree ages in excess of 360 years at breast height (Fiedler and Morgan, unpublished data). The sample of 96 trees from these sites contained 22 trees > 120 years at breast height. All but four of these 22 trees had a dbh > 15 in. The average age at breast height of sampled trees in the 16-inch diameter class was 115 years (Fiedler and Morgan, unpublished data). Trees with dbh ≥ 15 in were chosen for study as old growth on the assumption that most trees > 120 years old would have attained that diameter.

Site Selection and Descriptions

Approximately 45 state-owned sections in the Bull Mountains were initially considered. Over half of these sections were completely deforested by the 1984 (Hawk Creek) wildfire that consumed over 120,000 acres. Remaining sections known by foresters at the DNRC Southern Land Office to be forested with areas of relatively large diameter, "yellow-bellied" trees and containing no recent tree harvesting were considered potential locations of old-growth sites.

Potential old-growth sites were defined as areas exhibiting the following characteristics: many old trees with respect to the surrounding forest or grassland, many large trees showing signs of decadence or old age (broken or misshapen tops, bole defects, large diameter upper branches), several large snags and logs, and no evidence of timber harvesting. Potential sites were restricted to state-owned lands because of time constraints and because Montana DNRC guaranteed access, provided information about the sites, and expressed interest in the study.

An attempt was made to identify groves or stands of old trees in state sections using recent aerial photos. However, large old trees were not readily discernible from large-crowned trees using the available photos. Thus, identifying the population of old-growth sampling sites required preliminary walk-through site examinations. Thirteen state-owned sections potentially containing areas of old-growth ponderosa pine were initially identified by state foresters and examined (Table 2). Field reconnaissance of the thirteen sections confirmed ten groves in six of the sections as potential old-growth sampling sites. Five sites were then randomly selected for field sampling, with the constraint of only one grove per section.

Table 2:
State-Owned Sections in the Bull Mountains of Montana Examined for Potential Old Growth

Name	Township	Range	Section	Code
Sage Top	6N	24E	7	S
Rehder Creek	6N	26E	3	S
Road Coulee	6N	25E	16	N
(none)	6N	26E	16	N
Hay Coulee	7N	25E	36	S
Silver Bullet	7N	25E	16	S
Stag Run	7N	24E	36	C
Chimney Butte	8N	28E	36	S
(none)	8N	26E	14	N
No. 4 Mine	8N	26E	16	N
West Parrot Creek	8N	26E	36	U
Y Bar Coulee	8N	27E	36	N
Burnt Angus	9N	30E	36	N, C

Codes: S = sampled, N = no old growth, C = cutting evident, U = unsampled

Surveying and Sampling

Within each sample grove, a baseline along the azimuth of the grove's longest dimension was surveyed using a Criterion laser-surveying instrument. Four transects were then established, intersecting the baseline at right angles. The first transect was placed two chains (132 ft) from the origin of the baseline, and the remaining three transects at equidistant intervals along the length of the baseline (Figure 2), with a minimum of one chain (66 ft) between the last transect and the end of the baseline. Transects ranged from 175 ft to 740 ft in length, with a median length of 390 ft (Table 3). Strip plots 132 ft wide (66 ft on either side of the transect) extended the full width of the grove.

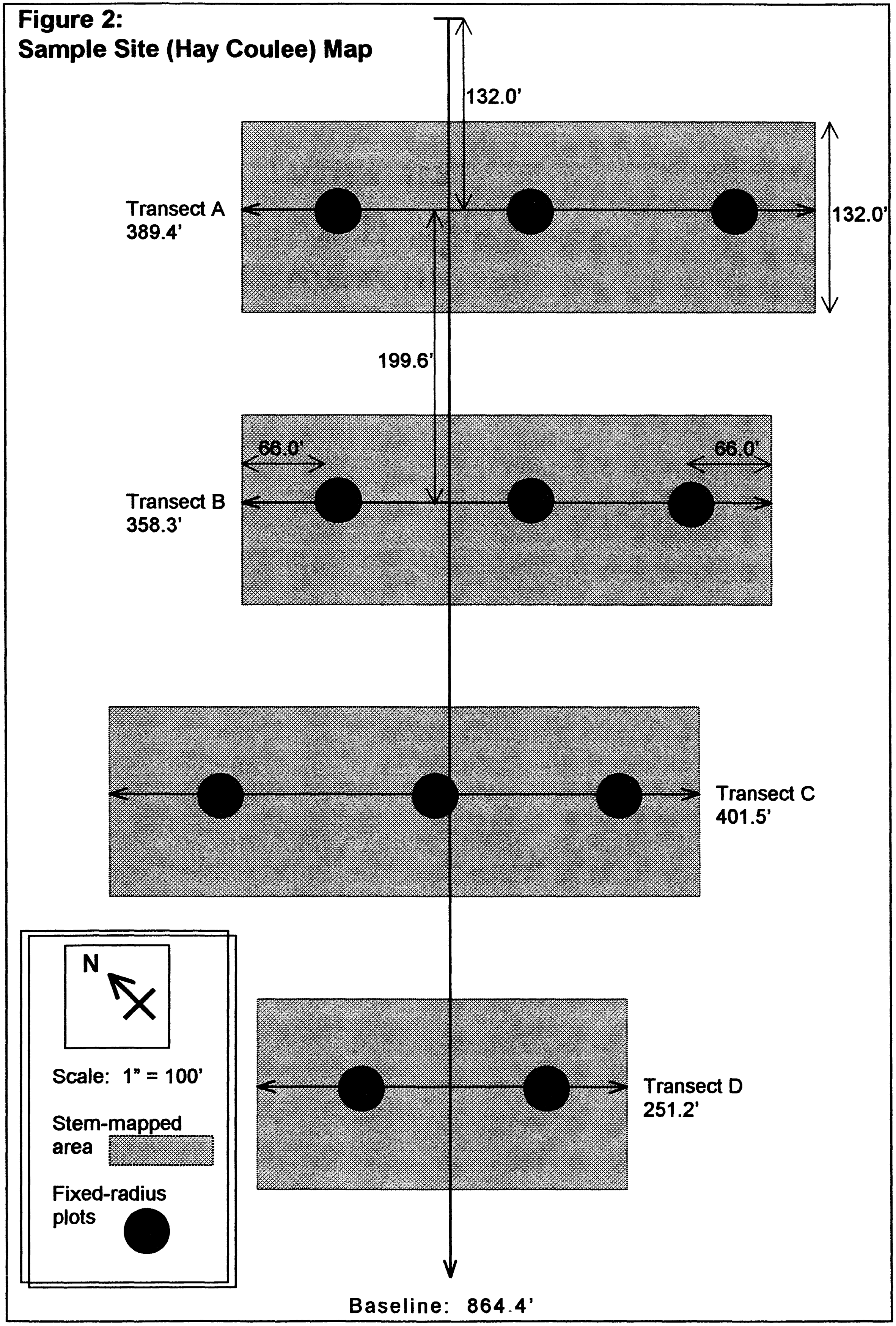
Table 3:
Transect Lengths and Spacing between Transects by Old-Growth Site

Transect	Sage Top (ST)	Hay Coulee (HC)	Chimney Butte (CB)	Silver Bullet (SB)	Rehder Creek (RC)
A	324.0	389.4	740.0	501.9	459.8
B	596.0	358.3	524.4	341.3	391.4
C	369.9	401.5	481.3	465.3	265.1
D	379.6	251.2	299.7	560.4	174.9
Spacing	132.0	199.6	352.0	151.8	175.0

Along each transect, downed logs ≥ 10 in diameter (at point of intersection with the transect) were counted. Length, diameter at intersection, and large end diameter were recorded for each log. The average number of logs per 300 ft of transect was calculated, and the weight (tons/acre) and volume (ft3/acre) were calculated (Howard and Ward 1972, Brown 1974).

Within each strip plot, a series of sampling points was established along the transect (Table 4). The first and last sampling points in each strip plot were located 66 ft from the beginning and end of the transect, respectively (Figure 2). All other sampling points were spaced equidistantly between the first and last point, with a minimum distance between points of 109 ft. Transect D at the

Figure 2:
Sample Site (Hay Coulee) Map



Rehder Creek site was not long enough to allow placing sample points 66 ft from the beginning and end of the transect and maintain 109 ft between points. Thus one sample point was placed at the midpoint of Transect D.

A fixed-area plot to sample small trees (< 5.0 in) and a variable-radius plot to sample trees ≥ 5.0 in were established at each sampling point. Seedlings (trees > 0.5 ft but < 4.5 ft in height) were counted, while saplings (trees ≥ 4.5 ft tall with dbh < 5 in) were counted and measured for diameter at each fiftieth-acre (16.7ft radius) fixed-area plot. A 10 BAF prism was used to identify "in" trees within each variable-radius plot, and the diameters of all live "in" trees ≥ 5.0 in were recorded (Avery and Burkhart 1994). Within a 66-ft radius of each sample point, the tree nearest the sample point in each 5-inch diameter class (dbh < 5.0 in, 5.0-9.9 in, and 10.0-14.9 in) up to 14.9 in was measured for diameter and cored at breast height.

Table 4:
Number of Sampling Points by Transect and Site for the Bull Mountains Old-Growth Sites

Transect	ST	HC	CB	SB	RC
A	2	3	6	4	4
B	5	3	4	4	3
C	3	3	4	4	2
D	3	2	2	4	1
Total	13	11	16	16	10

Within each strip plot, the locations of all live trees and standing dead trees (snags) with dbh ≥ 15 in (hereafter "large trees") were determined using a Silva

Ranger compass and 300 ft tape. The following data were recorded for each large tree and snag: aspect, position on slope, azimuth and distance from sampling point, dbh, total height, bole length, live crown ratio, crown shape, vigor class (Keen 1943, Thomson 1940, Hornibrook 1939), type of bole deformity, bark color and texture, and type, location, and size of scars.

Ten to fifteen large (live) trees in each strip plot were randomly selected for increment coring at breast height. Several snags were cored, but most contained pockets of rot. Increment cores were taken parallel to the contour on all trees to reduce variance and avoid compression wood and fire scars on the downhill and uphill sides of the bole, respectively. If an increment core did not appear to be near the pith or appeared to have a fire scar, branch, or other defect, the core was retained but a second core was taken 180° from the first. Each core was placed in a labeled plastic drinking straw for storage until it could be dried, mounted, and analyzed.

As shown in Table 5, 40 to 76% of the stand's acreage fell within the strip plots, and the sampling intensity was one to two point plots per acre of stand.

Table 5:
Stand Acreage and Sampling Intensity by Location for the Bull Mountains Old-Growth Sites

Stand attribute	ST	HC	CB	SB	RC
Stand acreage	7.24	6.90	15.48	7.42	5.27
Transect acreage	5.06	4.24	6.20	5.66	3.91
Percent stand in transect	70	61	40	76	74
Plots per acre of transect	2.6	2.6	2.6	2.8	2.6
Plots per acre of stand	1.8	1.6	1.0	2.2	1.9

Laboratory Methods

Stand tables were constructed according to Avery and Burkhart (1994), using the variable-radius plot tree counts for the calculation of basal area per acre, and for trees per acre by one-inch diameter classes (trees ≥ 5.0 in dbh). Densities of seedlings and saplings and of trees in one-inch classes from 1.0 in to 4.9 in were calculated with data from the fixed-radius plots.

Age and Growth Analysis

Increment cores were air-dried, mounted in labeled grooved boards, and sanded with progressively finer grit sandpaper (150 to 1500 grit) until individual earlywood cells could be identified using a dissecting microscope (Stokes and Smiley 1968). For each core, all rings (beginning with 1997) were counted and decadal radial growth was measured to the nearest 0.0001 inch using the ACU-GAGE Coordinate Measuring Machine and Javelin Smart Cam video system at the Intermountain Fire Sciences Laboratory, Missoula, Montana. The age and decadal radial increments of each core were recorded. If a tree was cored twice at breast height, the older age was recorded for the tree, and the decadal increments were averaged to create a single growth record for the tree. In the event that fire scar, rot, or other damage to the core was identified, the portion of the core predating the damage was not used in decadal increment measurements to avoid attributing growth to the wrong time period. Increment cores from snags were not used in growth analyses to avoid attributing growth to the wrong time period. Cores with rot were used for age analysis only if enough of the core appeared to be intact to avoid dramatically underestimating tree age.

Three measures of growth were examined: decadal radial increment (inches of radial growth per decade), decadal basal area increment (square feet of basal area growth per decade), and periodic percent basal area growth (average annual basal area increment for the period 1988 to 1997, expressed as a percent of total inside bark basal area in 1987). Decadal ring-width increments were averaged by decade to produce a master radial increment chronology. Decadal basal area increment (BAI) was calculated from radial increments for each tree (Phipps and Whiton 1988), and a master BAI chronology was developed.

Long-term growth trends were analyzed by plotting decadal radial increment against time for large trees, small trees, all trees, and large trees during the small tree period. The small tree period was defined as the decades (1788 to 1997) for which radial increments were available for at least five different trees < 15.0 in. Using a two-sample difference-of-means test (Barber 1988), average decadal growth rates during the 120 years since Euro-American settlement (1878 to 1997) were compared to average decadal growth rates during the 120-year period prior to settlement (1758 to 1877) and to average decadal growth rates during the first 12 decades of each tree's life.

Stem Mapping and Spatial Analysis

Point pattern maps are two-dimensional representations of objects that are very small relative to the distances between them and the extent of the area in which they occur. Such maps are examined to discover something about the processes that generated the pattern (Boots and Getis 1988), and clear description of spatial pattern is essential to understanding the scales of ecological processes (Dale 1999). Point pattern maps of the large trees and snags were developed from the strip plot surveys at all sites. For each large tree or snag, a coordinate (x, y) was calculated from the survey data, and the coordinate was plotted as a point within the stand.

The study of the location of points in a pattern with respect to the study area is known as *dispersion* analysis (Boots and Getis 1988). Two basic techniques exist for conducting dispersion analysis: quadrat methods and distance methods (Boots and Getis 1988). Three distance methods (the G empirical distribution function, Clark and Evans' aggregation index, and Pielou's index of nonrandomness) and one quadrat method (Greig-Smith mean/variance ratio) were used to discern statistically whether the large trees at each site were dispersed randomly, uniformly, or in clusters.

A pattern of plants which meets the two homogeneous planar Poisson point process conditions is said to possess complete spatial randomness (CSR). The homogeneous planar Poisson point process conditions are: 1) each location in the study area has an equal chance of receiving a plant(uniformity); and 2) the selection of a location for a plant in no way influences the selection of location for any other plant (independence) (Boots and Getis 1988, Cressie 1993). Because of the variety of interactions between plants, we do not expect their positions to be independent of each other, but it is possible that their dispersion appears random (Dale 1999). The null hypothesis (H_o) was: the pattern under investigation has CSR. The confidence level was 0.05 for the examples. Failure to reject the null hypothesis suggests that the plant pattern under investigation was not significantly different from CSR. Rejection of the null hypothesis suggests that the plant pattern was different from CSR (Boots and Getis 1988), and the value of the statistic suggests whether or not the pattern was regular or clustered.

Explanation of Statistics Used

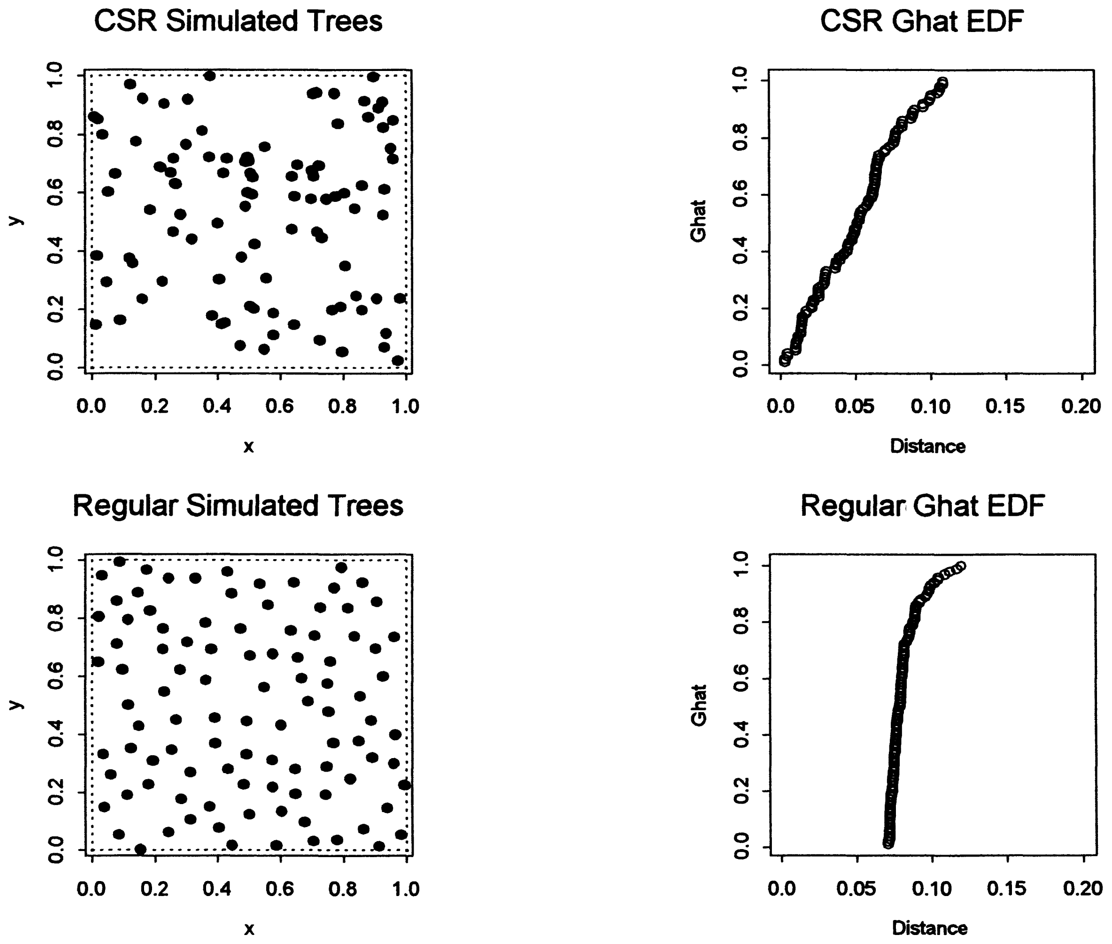
The G empirical distribution function (G EDF) and aggregation index are nearest neighbor distance methods, which examine nearest neighbor distances of plants to other plants. Nearest neighbor analysis examines the distance between each plant in the pattern and the closest plant to it (Clark and Evans 1954, Boots and Getis 1988, Cressie 1993, Pretzsch 1997). A major draw-back of many nearest neighbor methods is that they provide no information on the size or spacing of clumps (Dale1999). The nearest neighbor distance (d_i) for each sample plant (i) and the mean nearest neighbor distance (d_{obs}) were calculated using the Spatial Statistics Module of the S-Plus statistical software package.

G Empirical Distribution Function

The G empirical distribution function is not commonly used in scientific literature because it does not use information in the pattern over a wide range of scales (Cressie 1993). However, the G empirical distribution function (G EDF) provides a visual method of approximating the distribution of observed nearest neighbor distances, and can be readily calculated and graphed in S-Plus. Thus it will be demonstrated using simulated plant patterns with known patterns of dispersion, and the visual results of the simulations will be verified by the aggregation index. The form of the G EDF is: $\hat{G}(d) = \sum_{n=1}^{n} 1(d_i \leq d) / n, \ d > 0$, where n is the number of plants in the pattern, and d_i denotes the distance from the i^{th} plant to its nearest neighbor (Kaluzny *et al.* 1998, Cressie 1993). Thus the nearest neighbor distance for each plant in the pattern is indicated by its position along the x-axis, and the y-axis indicates the proportion of trees in the pattern with an equal or lesser nearest neighbor distance.

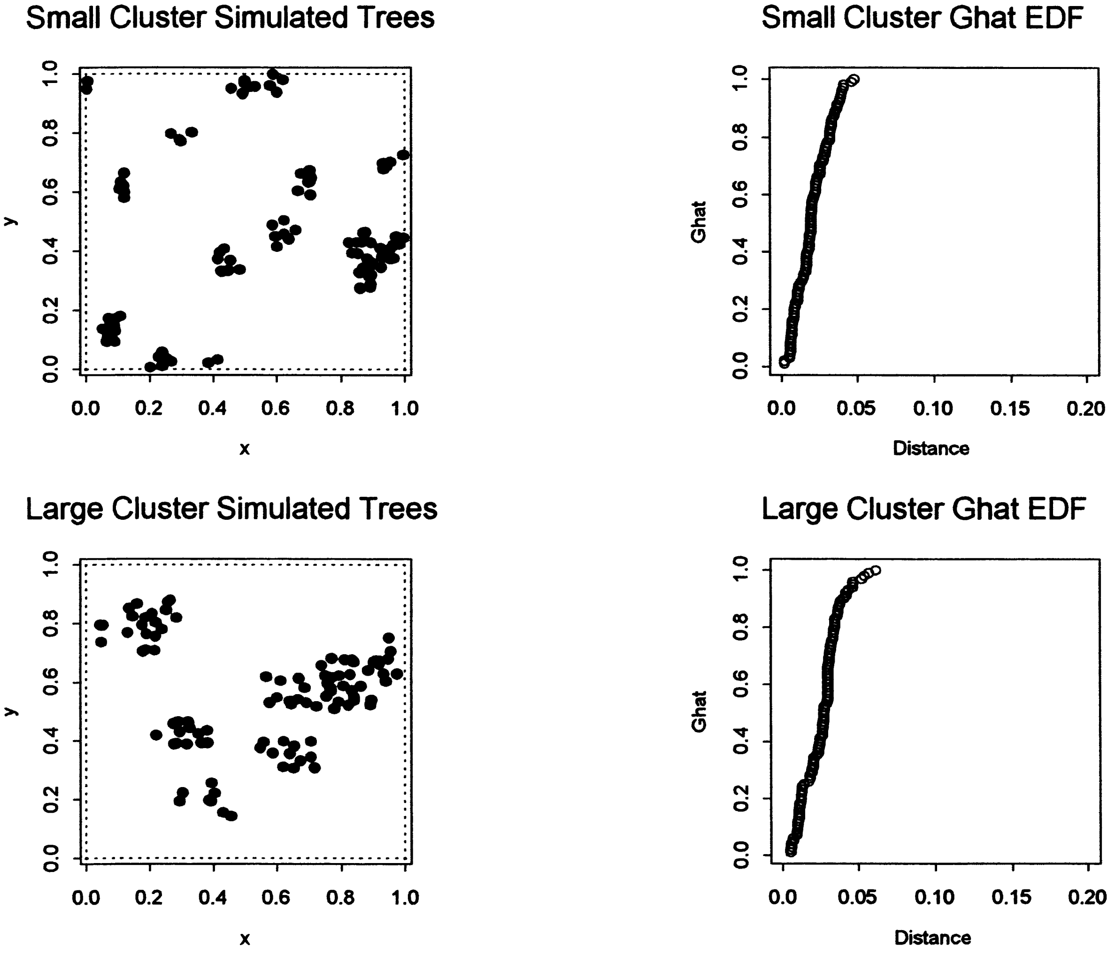
Figures 3 and 4 demonstrate how the shape of the G EDF varies according to the dispersion of the plants in a give area. For a spatially random distribution of plants (upper plots in Figure 3), the shape of the G EDF is quite angular with nearest neighbor distances spanning a relatively large range of distances. Whereas, for a regular or uniform distribution (lower plots in Figure 3), the shape of the G EDF is nearly vertical, with a relatively high proportion (65%) of plants at the distance which corresponds to the most common nearest neighbor distance (Distance = 0.07 in example).

Figure 3:
Random and Regular Plant Pattern Simulations



The clustered G EDF plots (Figure 4) show slightly angular shapes, with the range of nearest neighbor distances less than that of the random distribution but increasing with the size of the clusters. Thus, nearest neighbor distances span a slightly larger range for the large clusters than for the small clusters. In order to

Figure 4:
Clustered Plant Pattern Simulations



Small Cluster Simulated Trees

Small Cluster Ghat EDF

Large Cluster Simulated Trees

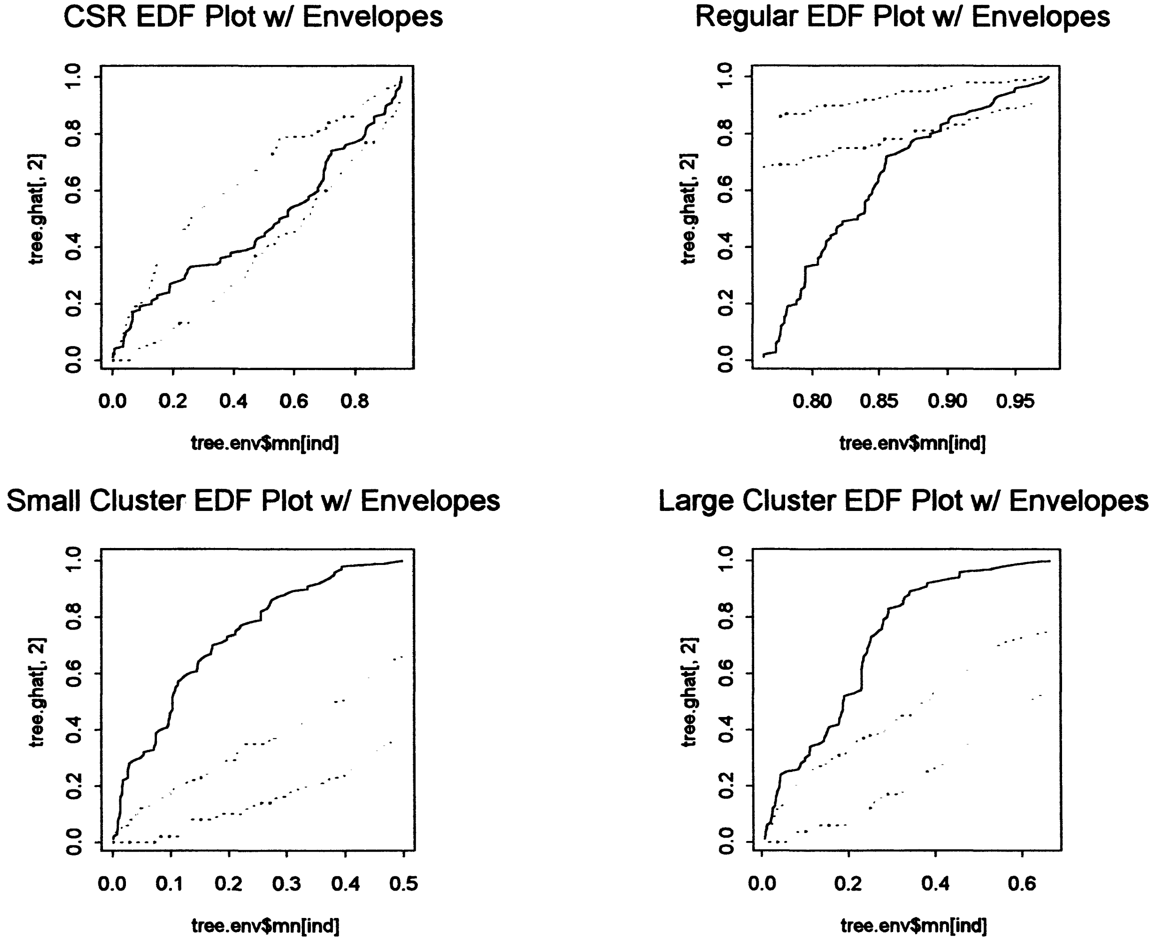
Large Cluster Ghat EDF

make comparisons between patterns using plots of the G EDF's, it is necessary to scale the x-axis ("Distance") alike on all plots; otherwise, it is difficult to detect differences in the shapes of the G EDF's.

To evaluate the significance of the G EDF, a Monte Carlo test procedure can be used. The Monte Carlo procedure involves generating a (simulated) set of CSR patterns each with the same number of plants as the empirical pattern, in an area of the same dimensions as the empirical pattern (Boots and Getis 1988). Using maximum and minimum values of the G EDF for the Monte Carlo CSR patterns, a simulation envelope is created (Kaluzny *et al.* 1998, Cressie 1993). The G EDF and the minimum and maximum Monte Carlo functions are plotted as a quantile-quantile (Q-Q) plot, with the simulated values on the x-axis and empirical values on the y-axis (Cressie 1993). Examples of G EDF plots with CSR simulation envelopes are shown in Figure 5 for the four plant patterns discussed.

If the plotted G EDF lies within the simulation envelope, as shown in the upper left plot of Figure 5, then the G EDF is not significantly different from CSR. If the plotted G EDF passes through the lower boundary of the simulation envelope, as in the upper right plot of Figure 5, the H_o is rejected and the plant pattern is said to be uniform. The lower two plots show that the plotted G EDF passes through the upper boundary of the simulation envelope for clustered plant patterns.

Figure 5:
Plots of G Empirical Distribution Functions with Monte Carlo CSR Envelopes



CSR EDF Plot w/ Envelopes

Regular EDF Plot w/ Envelopes

Small Cluster EDF Plot w/ Envelopes

Large Cluster EDF Plot w/ Envelopes

Aggregation Index

The Clark and Evans aggregation index is rather famous and has been used in ecological studies for over forty years (Dale 1999). Clark and Evans (1954), Ripley (1981), White (1985), Boots and Getis (1988), and Pretzsch (1997) describe the aggregation index (R) as the ratio between the observed average distance (d_{obs}) of a plant to its nearest neighbor and the expected average distance (d_{exp}) for a random plant distribution of the same size, number of plants (N), and area (A): $R = d_{obs} / d_{exp}$. If the plants have CSR distribution, then R = 1. If the plants are clustered, d_{obs} will be less than d_{exp}, and $R < 1$. If the plants have a regular or uniform distribution, then d_{obs} will be greater than d_{exp}, and $R > 1$. Table 6 displays the d_{obs}, d_{exp}, and R values for the simulated plant patterns discussed above.

Table 6:
Aggregation Index (R) for Plant Pattern Simulations

Simulation	A	N	d_{exp}	d_{obs}	R	z_{calc}
CSR	1	100	0.05	0.0507	1.01	0.268
Regular	1	100	0.05	0.0811	1.62	11.900
Small Cluster	1	100	0.05	0.0204	0.41	-11.326
Large Cluster	1	100	0.05	0.0260	0.52	-9.183

A = area, N = number of plants, d_{exp} = expected average nearest neighbor distance, d_{obs} = observed average nearest neighbor distance, R = ratio of d_{obs} to d_{exp}, z_{calc} = calculated z statistic.

The observed and expected average nearest neighbor distance values may be compared using a normally distributed z statistic: $z_{calc} = [d_{obs} - d_{exp}]/[0.0683\ A/N^2]^{0.5}$. If the absolute value of the calculated z is greater than the z value from tables of the Normal distribution for a given alpha level, then H_o can be rejected at that alpha level. For these examples, the alpha level was 0.05 and the corresponding z from tables of the Normal distribution is 1.96 (Boots and Getis 1988). As the last column in Table 6 shows, the absolute value of z_{calc} is greater than 1.96 for all simulations other than CSR. Thus the null hypothesis is rejected at the 0.05 level for all simulations except the CSR pattern. The results of the aggregation index agree with the G EDF results for the four simulated point patterns.

Index of Nonrandomness

Pielou (1959) describes the index of nonrandomness (α) as a nearest neighbor analysis that examines the distances between randomly selected points and the plant which is closest to each point. Selection of the sampling plot centers in the field was assumed to be unbiased, and the distance (w_i) from each sampling point to the large tree nearest it was used to calculate α for all sites, using the equation: $\alpha = \pi D w$. The density (D) of the large trees (number per ft^2) was determined independently (from the count of large trees per acre of transect), and w is the mean of the squares of the point-to-plant distances (w_i). Where n equals the number of random sampling points from which the distances were measured, α equals $(n-1)/n$ if the population is randomly arranged. If the stand is uniformly arranged, $\alpha < (n-1)/n$; while $\alpha > (n-1)/n$ if the stand is clustered. Since $2n\alpha$ is Chi-square distributed with 2n degrees of freedom, the significance of the difference between α and $(n-1)/n$ is found by constructing confidence intervals for α for any desired significance level (Pielou 1959).

Variance/Mean Ratio

The variance/mean ratio (Greig-Smith 1964) is a quadrat method of dispersion analysis. The transects at each site were divided into a number (N) of tenth-acre (66 ft x 66 ft) quadrats, and the number of large trees within each quadrat was recorded. Then the mean (M) and variance (V) of the number of trees per quadrat were calculated for each stand. If the pattern of large tree dispersion is not different than random, then the variance/mean ratio will equal one, because in a Poisson probability distribution, the value of the mean is expected to equal the variance (Boots and Getis 1988). If the pattern is uniform, each quadrat will contain a similar number of trees and the variance will be less than the mean. Clustered patterns will reveal many quadrats with no trees and a few quadrats with many trees. Thus the variance of the number of trees per quadrat will exceed the mean number of trees per quadrat (Boots and Getis 1988). The statistic may be tested with a t-statistic: $t = (V - M)/(2/(N-1))^{0.5}$ (Boots and Getis 1988). The calculated value of t is compared to the t-value from a statistical table for a stated significance level, using N-1 for the degrees of freedom. If the absolute value of t is less than the t-value from the table, then the null hypothesis cannot be rejected. If the absolute value of the calculated t exceeds t, then the null hypothesis can be rejected, and the pattern is clustered if the calculated value of t is positive. If the calculated value of t is negative, then the pattern is uniform.

Results and Discussion

Site Attributes

Details of each sampled old-growth site are shown in Table 7. All sites were classified within the *Pinus ponderosa/Agropyron spicatum* habitat type (Pfister *et al.* 1977) with the exception of Rehder Creek (RC), which was classified as a more mesic *Pinus ponderosa/Prunus virginiana* habitat type (Pfister *et al.* 1977). Sites were located on a variety of aspects and slopes, followed coulees, or occurred entirely within larger drainage features. Elevation of all sites was between 3500 ft and 3900 ft.

Table 7:
Site Attributes for the Old-Growth Sites in the Bull Mountains of Montana

Attributes	Sage Top (ST)	Hay Coulee (HC)	Chimney Butte (CB)	Silver Bullet (SB)	Rehder Creek (RC)
Habitat type	PIPO/ AGSP	PIPO/ AGSP	PIPO/ AGSP	PIPO/ AGSP	PIPO/ PRVI
Aspect(s)	SW, S, NW	S,SW,SE	E, N, S	N, NW, NE	N, NE
Slope	17 - 35%	15 - 25%	9 - 15%	5 - 20%	20 - 40%
Shape	concave	concave	concave	flat	concave
Elevation	3600 ft	3700 ft	3500 ft	3500 ft	3900 ft
Recent grazing	Y	Y	Y	Y	N
Cutting w/ in 1 mile	N	Y	Y	Y	Y
Marked to be cut	N	N	Y	Y	N

All sites except Rehder Creek revealed signs of recent grazing and have likely been grazed for decades, considering regional land use history. Rehder

Creek was likely not grazed because of the steep slopes and dense vegetation. Recent forest management activities (timber marking and cutting) were evident within the section surrounding the old-growth stands at all sites except Sage Top (ST), which was very dry, steep, and offered fairly poor quality timber and sparse regeneration (Table 9). Two stands, Silver Bullet (SB) and Chimney Butte (CB), were marked for harvesting and have been logged since 1998.

Stand Attributes

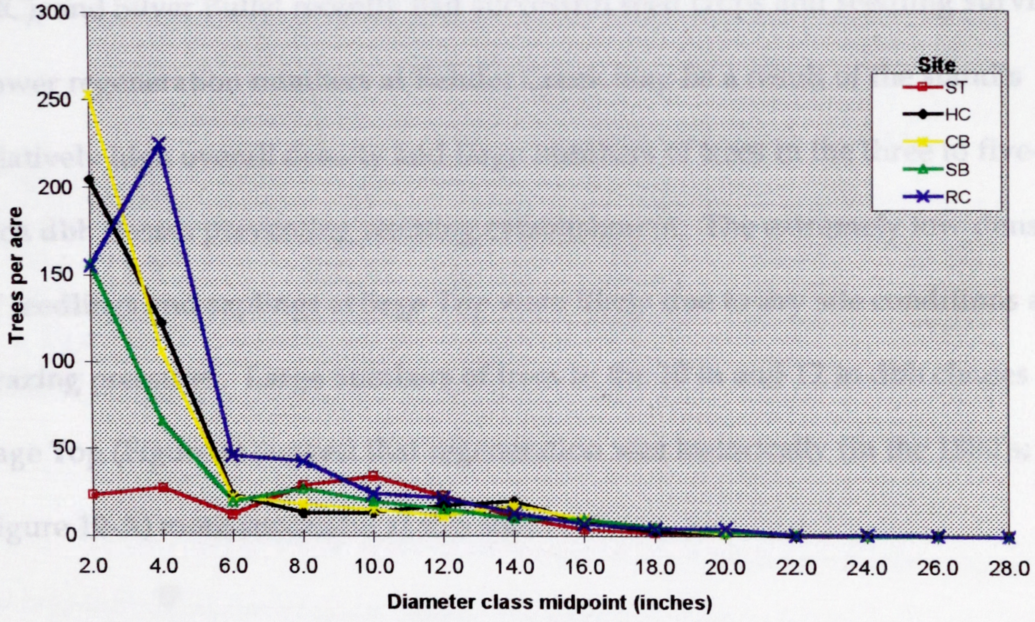
Data on trees per acre (tpa) by diameter class are displayed in Table 8 and Figure 6 for the five sites. Density of trees ≥ 5.0 in diameter ranged from 98 tpa at Sage Top to 165 tpa at Rehder Creek. With the exception of Sage Top, all sites revealed an inverse-J diameter distribution of trees per acre (Figure 6) typical of

Table 8:
Trees Per Acre by Five-Inch Diameter Class and Site

Size class	ST	HC	CB	SB	RC
1.0 - 4.9"	50.00	327.27	359.38	221.88	380.00
5.0 -9.9"	56.13	43.75	49.11	61.13	105.59
10.0 - 14.9"	50.30	42.78	36.28	32.46	43.14
15.0 - 19.9"	6.35	10.88	15.24	15.96	12.48
≥ 20.0"	0.51	1.42	2.45	1.54	4.26
Total ≥ 5.0"	113.29	98.83	103.08	111.09	165.47

uneven-aged old-growth forest stands (Oliver and Larson 1996). All sites had fewer than 5 tpa with dbh ≥ 20.0 in. With the exception of Sage Top, all sites had over 200 tpa with dbh < 5.0 in. The relatively low abundance of small trees (dbh < 5.0 in) at Sage Top may be attributable to several factors: dry site conditions, poor seed crops, or soil compaction and seedling mortality due to livestock.

Figure 6:
Trees per Acre by Diameter Class and Site



Density of trees ≥ 15.0 in diameter ranged from 6.5 tpa to 18 tpa among the five sites. Chimney Butte and Silver Bullet had the most large trees per acre, while Sage Top had the fewest. Green *et al.* (1992) state that 4 tpa ≥ 17 in is a Forest Service minimum characteristic for east-side Montana old-growth ponderosa pine stands. Mehl (1992) notes that a minimum of 10 trees per acre of dbh ≥ 16 in is a standard old-growth attribute of interior ponderosa pine cover types in the Front Range and Black Hills. The abundance of trees ≥ 15 in at the Bull Mountains old-growth stands suggests that, with the exception of Sage Top, the large tree densities meet Forest Service descriptions of old-growth ponderosa pine in the Rocky Mountain Region.

Current regeneration (Table 9) suggests that Chimney Butte, Hay Coulee (HC), and Silver Bullet recently had successful seed crops and seedling survival. Lower regeneration numbers at Rehder Creek may be a result of the stand's relatively high overall density and large numbers of trees in the three to five-inch dbh classes preventing seedling establishment. The extremely low densities of seedlings and saplings at Sage Top were likely due to dry site conditions and grazing pressures. Large numbers of trees in the 10 in and 12 in dbh classes at Sage Top (Figure 6) suggest that regeneration was historically (in the 1880's; see Figure 10-A) more successful at this site.

Table 9:
Regeneration: Stems per acre by Size Class and Site

Regeneration	ST	HC	CB	SB	RC
Seedlings (height < 4.5')	4	1295	2056	772	380
Saplings (dbh < 5.0")	54	355	656	266	390

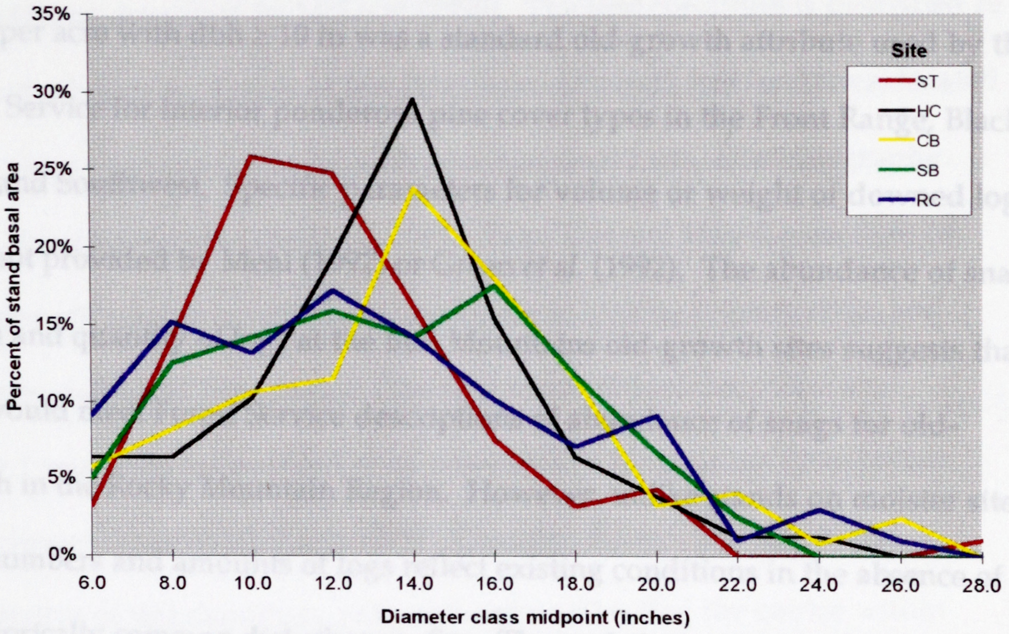
Table 10 shows stand density in square feet of basal area per acre (ft^2/ac) by five-inch diameter classes for the old-growth sites. As with tpa, Rehder Creek had the greatest density and Hay Coulee the least in terms of basal area. Trees ≥ 15.0 in diameter accounted for 16 to 40 percent of the basal area in each stand. Since basal area and volume are highly correlated (Avery and Burkhart 1994), this finding suggests that the majority of each stand's wood volume was in trees < 15.0 in diameter.

Table 10:
Basal Area Per Acre (ft^2) by Diameter Class and Site

Size class	ST	HC	CB	SB	RC
5.0 -9.9"	20.77	12.73	13.75	19.38	32.00
10.0 - 14.9"	39.23	38.18	31.88	26.88	36.00
15.0 - 19.9"	10.00	16.36	23.75	25.00	20.00
≥ 20.0"	1.54	3.64	6.88	3.75	11.00
Total	71.54	70.91	76.26	75.01	99.00

Figure 7 graphically depicts the proportion of each stand's total basal area by two-inch diameter-classes. Relatively high proportions of basal area occured in the 10 in and 12 in diameter classes at Sage Top, and in the 14 in and 16 in classes at Hay Coulee and Chimney Butte. Silver Bullet and Rehder Creek exhibited more even distributions of basal area across trees in the 8 in to 16 in classes.

Figure 7:
Proportion of Stand Basal Area by Diameter Class and Site



Densities of large (dbh ≥ 15.0 in) standing dead trees (snags) and downed logs (diameter ≥ 10.0 in) at each site are shown in Table 11. Snag densities ranged from a low of 1.5/ac at Sage Top to a high of 3.2/ac at Silver Bullet. The number of downed logs per 300 ft of transect ranged from 0.6 (Sage Top) to 1.8 (Hay Coulee). Volumes and weights of downed logs were between 67 ft³/ac and 1.0 tons/ac at Sage Top and 304 ft³/ac and 4.6 tons/ac at Hay Coulee.

Large downed logs and snags have been noted as important structural components of old-growth stands, though abundance, size, and rate of deterioration depend upon location, climate, species composition, and fire history (Moir 1992, Duchesne 1994, Oliver and Larson 1996). Green *et al.* (1992)

found 5 to 10 snags per acre > 9 in during screening of old-growth ponderosa pine sites in the Lewis and Clark National Forest. Mehl (1992) noted that two snags per acre with dbh ≥ 10 in was a standard old-growth attribute used by the Forest Service for interior ponderosa pine cover types in the Front Range, Black Hills, and Southwest. Specific parameters for volume or weight of downed logs were not provided by Mehl (1992) or Green *et al.* (1992). The abundance of snags ≥ 15 in and quantity of logs at the Bull Mountains old-growth sites suggests that they would meet Forest Service descriptions of abundance of snags for old-growth in the Rocky Mountain Region. However, unlike stands on moister sites, snag numbers and amounts of logs reflect existing conditions in the absence of an historically common disturbance--fire. Thus existing amounts of snags and downed logs may be well above historic levels, and not necessarily appropriate targets for long-term management of old-growth ponderosa pine on drier sites. From an ecological perspective, the amounts of coarse woody debris should vary among sites considering differences in topography, disturbance, and stand densities (Moir 1992).

Table 11:
Large Snags (dbh ≥ 15.0 in) and Downed Logs(≥ 10.0 in) by Site

	ST	HC	CB	SB	RC
Snags/ acre	2.17	1.65	2.42	3.18	2.56
Logs/ 300'	0.63	1.79	1.06	0.98	1.52
Log volume (ft^3/ acre)	67	304	148	174	150
Log weight (tons/ acre)	1.0	4.6	2.3	2.7	2.3

The old-growth site and stand attributes described in this study fit the three conditions described by McLeod (1999). The first condition is described as old individual trees or clumps of trees that have survived {surface} fires, located on rocky ridges and south slopes, with discontinuous fuels, and topography defining stand boundaries (McLeod 1999). Sage Top and Hay Coulee best fit this old growth condition with their south aspects, patchy regeneration, and topography-delimited boundaries. The second condition, described as a "stringer," reveals occasional old trees growing in a long, linear distribution along drainage features (McLeod 1999). Chimney Butte is the site most representative of this condition, with its baseline bisecting the coulee within which the old growth occurred. McLeod describes the third condition as a few old trees scattered throughout an uneven-aged stand on northerly slopes, with a dense understory of recent regeneration and small sawtimber. Rehder Creek best fits this condition as a densely stocked site located on a north aspect.

McLeod (1999) notes that the three conditions are similar and that "none of the conditions can be characterized as distinct, identifiable stands of even-aged old trees." For this reason it is often difficult to delineate an old-growth stand as a separate entity from the uneven-aged matrix within which it occurs. Silver Bullet exemplifies this fuzzy distinction, fitting either of the last two conditions with an edge following a coulee, northerly aspects, a relatively low proportion of older trees, and in an uneven-aged condition.

Large Tree Attributes

A total of 413 large (dbh ≥ 15.0 in) trees and snags over five sites were stem mapped and had crown, bole, and other morphological features recorded. Increment cores from 193 large trees and snags and 200 small (dbh < 15.0 in) trees were used in age analysis. Twenty-two trees contained heart rot, and 15 were not included because the rot prevented an accurate assessment of total age. The average number of countable rings on cores of trees with heart rot was 187. The 15 rejected cores possessed between 117 and 183 annual rings, while the seven cores retained had between 203 and 358 rings. Only two of the partial cores possessed less than 120 annual rings, suggesting that ages of trees with heart rot typically exceed 120 years. Table 12 indicates that 94% of the large (≥ 15.0 in) trees sampled for age were ≥ 120 years at breast height. Across all sites, 38% of the large trees were ≥ 200 years and 17% were ≥ 300 years. Only two trees sampled for age were found to be greater than 400 years at breast height.

Large tree ages at the Bull Mountains sites readily meet the 180-year and 160-year minimums cited by Green *et al.* (1992) and Mehl (1992) for old-growth ponderosa pine in eastern Montana and the Black Hills, respectively. Maximum ages at these five sites also suggest that these stands may represent the oldest-of-the-old for DNRC lands in the Bull Mountains because of the large 1984 stand-replacing wildfire.

Table 12: Percent of Large (≥ 15.0 in) Live Trees by Breast Height Age Class for the Bull Mountains Old-Growth Sites

Age class	ST	HC	CB	SB	RC	ALL
< 120 yrs	0	9	4	5	13	6
≥ 120 yrs	100	91	96	95	87	94
≥ 200 yrs	79	40	29	14	45	38
≥ 300 yrs	39	17	18	9	8	17

Age structure (20-year classes) of large trees is depicted in Figure 8 for all five old-growth sites combined. The number above each bar is the number of trees in that age-class. More than half (54.9%) of the large trees were 120 to 200 years old, with few trees younger than 120 years, and a gradually decreasing number older than 200 years. The lack of gaps in the age distribution (until the 430-year age-class) despite the variable distribution of ages indicates fairly successful, though sporadic, regeneration and survival of large trees across the Bull Mountains sites throughout the past 400 years.

Age structure of small (dbh < 15.0 in) trees across all five sites is displayed in Figure 9. The number of trees in each 20-year age-class is again indicated above each bar. Only 3.5% of the small trees were over 200 years old, the smallest of which was 11.5 in. Although a third of the small trees had a dbh < 5 in, nearly three quarters (73%) were between 20 and 120 years, and only 3% were between 1 and 20 years old, suggesting that initial height and diameter growth of small trees was quite slow.

Figure 8:
Percent of Large Trees (dbh >14.9 in) by Breast Height Age Class

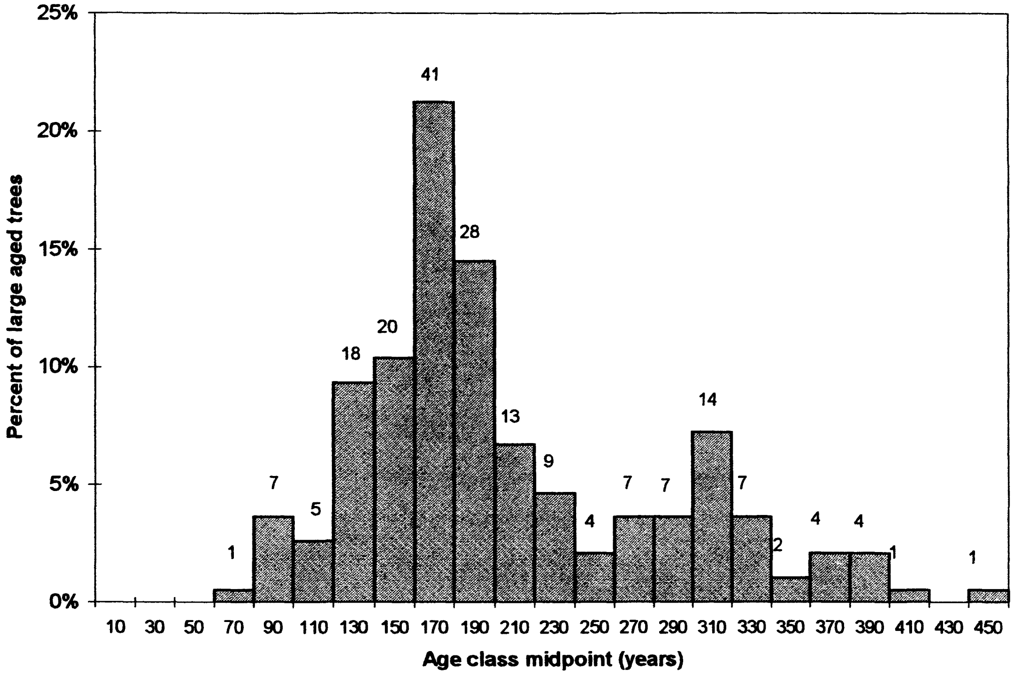
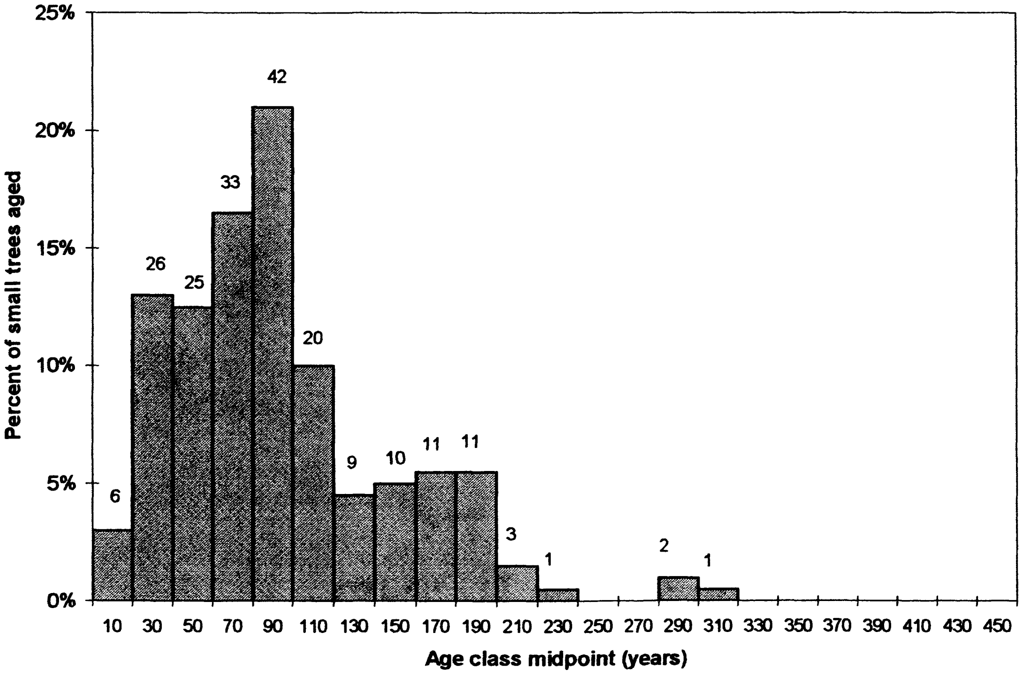


Figure 9:
Percent of Small Trees (dbh < 15.0 in) by Breast Height Age Class



A total of 98 large trees was sampled for age at breast height (4.5 ft above ground line on uphill side) and age at stump height (1.0 ft to 1.5 ft above ground line on uphill side). Of the 98 trees sampled, only 51 revealed a stump height age greater than breast height age. The small proportion of stump height ages exceeding breast height ages resulted from difficulties in accurately locating and successfully reaching the pith with the increment borer at stump height. Both breast height *and* stump height piths were successfully reached in only 2 trees, revealing age differences of 9 and 10 years.

The 51 trees (≥ 15.0 in) successfully sampled were 80 to 324 years old at breast height and 87 to 331 years at stump height. The average breast height age was 189.0 years, and the average stump height age was 205.6 years. The mean age difference between stump and breast height samples was 16.7 years. Thus, approximately 10 to 20 years were required for trees to grow from stump height to breast height, indicating approximate early height growth rates of only 0.15 ft to 0.35 ft per year for trees currently with dbh ≥ 15.0 in.

A scatter plot of breast height tree age vs. diameter for aged trees at all sites is shown in Figure 10. A moderate positive linear relationship ($R^2 = 0.58$) existed between breast height age and diameter. Individual site scatter plots of breast height age vs. diameter for aged trees are shown in Figures 10-A through 10-E. Fairly distinct age clusters (horizontal lines in Figures 10-B through 10-E)

Figure 10:
Scatter Plot of Breast Height Age vs. Diameter (all sites combined).
Solid line indicates linear regression of age vs. diameter;
dashed lines indicate possible regeneration pulses.

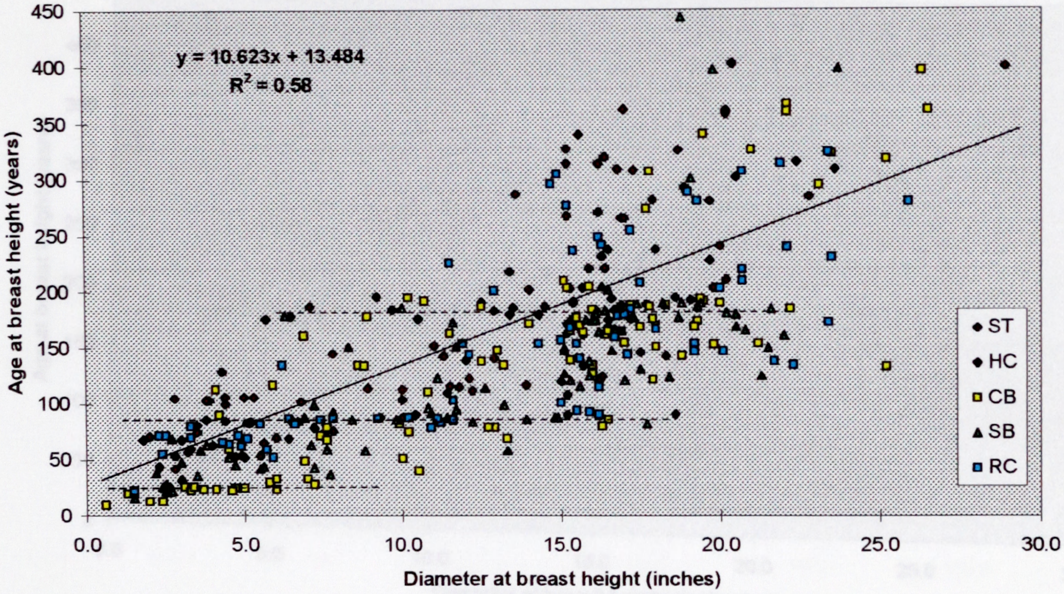


Figure 10-A:
Scatter Plot of Breast Height Age vs. Diameter (Sage Top).
Dashed line indicates possible regeneration pulse.

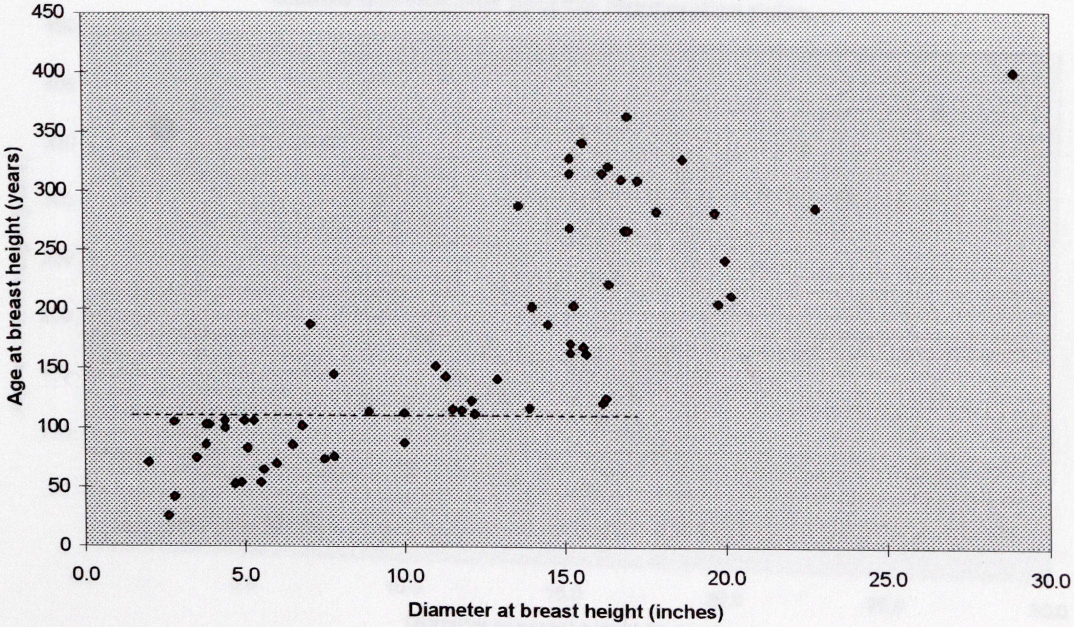


Figure 10-B:
Scatter Plot of Breast Height Age vs. Diameter (Hay Coulee).
Dashed lines indicate possible regeneration pulses.

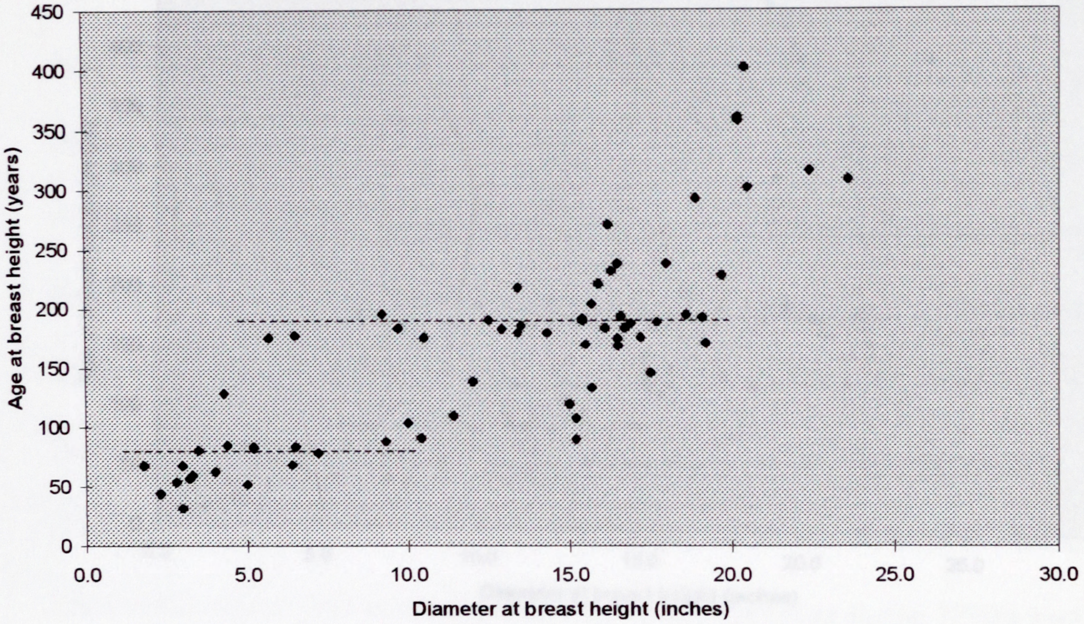


Figure 10-C:
Scatter Plot of Breast Height Age vs. Diameter (Chimney Butte).
Dashed line indicates possible regeneration pulse.

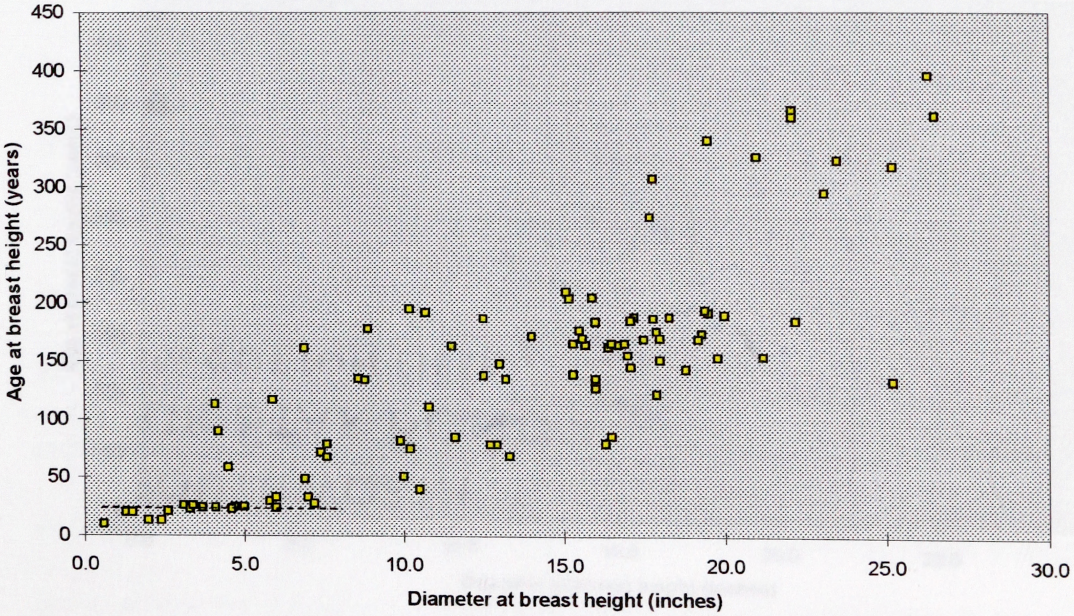


Figure 10-D:
Scatter Plot of Breast Height Age vs. Diameter (Silver Bullet).
Dashed lines indicate possible regeneration pulses.

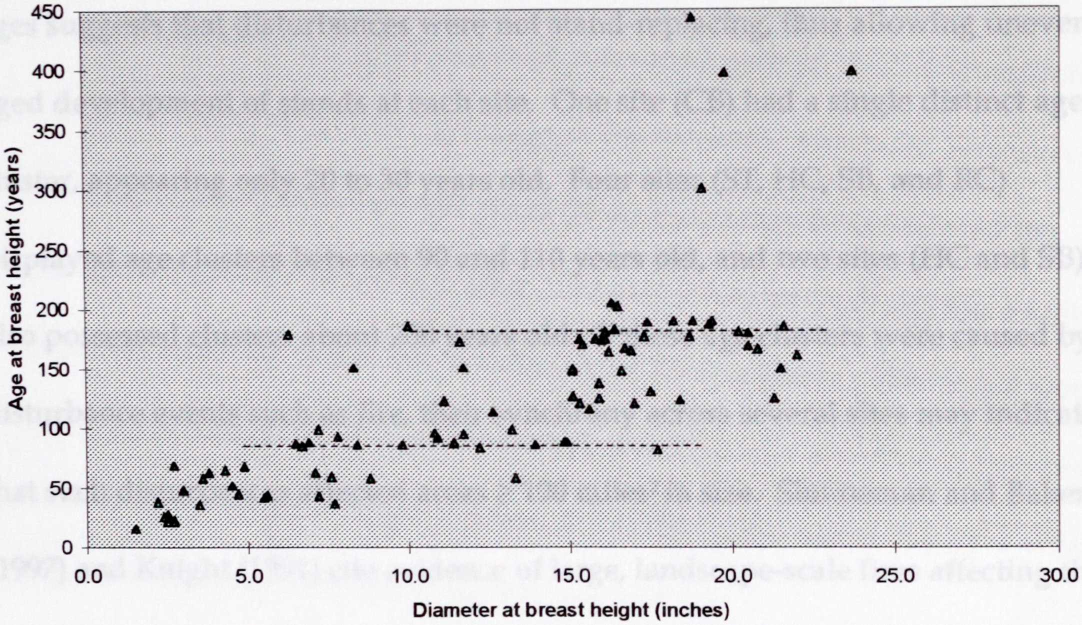
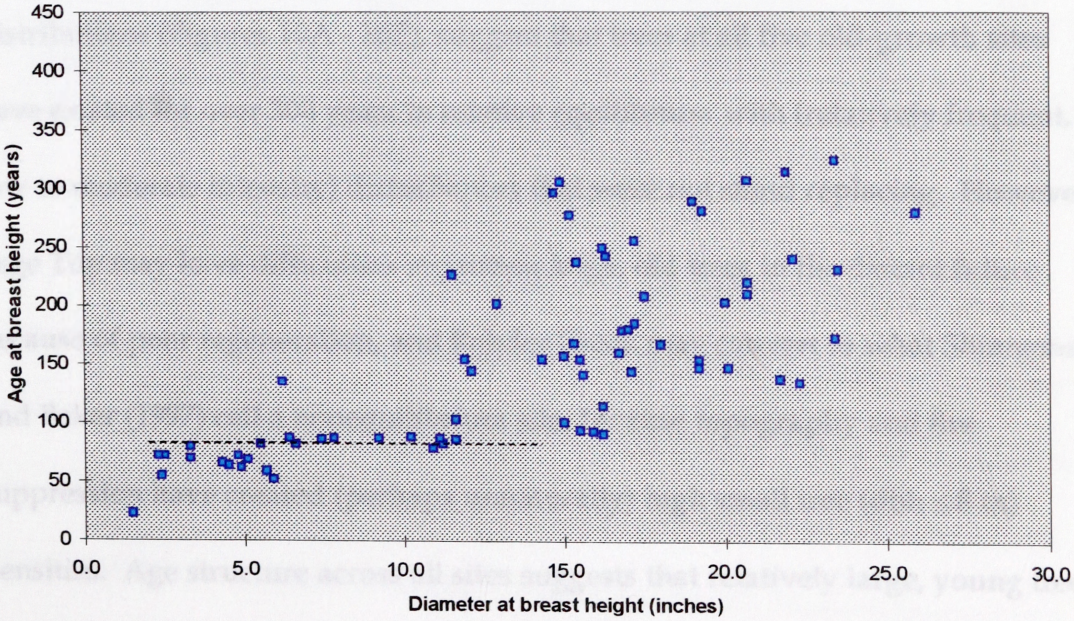


Figure 10-E:
Scatter Plot of Breast Height Age vs. Diameter (Rehder Creek).
Dashed line indicates possible regeneration pulse.



may indicate regeneration pulses resulting from abundant seed crops, disturbance events, or favorable climatic conditions. Wide distribution of tree ages suggests that disturbances were not stand-replacing, thus allowing uneven-aged development of stands at each site. One site (CB) had a single distinct age cluster, appearing only 20 to 30 years old. Four sites (ST, HC, SB, and RC) displayed age clusters between 90 and 110 years old, and two sites (HC and SB) also possessed clusters about 200 years old. If these age clusters were caused by disturbance events such as fire, their synchrony across several sites may indicate that such disturbances affected areas ≥ 100 miles^2 in size. Shinneman and Baker (1997) and Knight (1994) cite evidence of large, landscape-scale fires affecting the Black Hills region and mountains of northwest Wyoming in the 1790's and late 1800's.

Diameter distributions at individual sites (Figure 6), viewed with age distributions (Figures 10A - 10E), suggest that trees at all five old-growth sites have existed for over 300 years in relative equilibrium with (relatively frequent, low to moderate intensity) disturbances that were not stand replacing. However, Sage Top may have difficulties recruiting large, old trees in the distant future because of poor regeneration, and Rehder Creek may convert to what Shinneman and Baker (1997) call a nonequilibrium site, because topography and fire suppression have created (perhaps unnaturally) high small tree (dbh ≤ 8 in) densities. Age structure across all sites suggests that relatively large, young trees are available for continued existence of old growth throughout the Bull

Mountains, provided many of these trees are not lost to catastrophic disturbance or harvest.

Large tree age and maximum size attributes are displayed by site in Table 13. Both the oldest and youngest large trees aged were located at Silver Bullet, which exhibited the greatest age range of the five sites. However, because of the low proportion of trees over 200 years, Silver Bullet may be considered the youngest of the five old-growth sites. The tree of largest diameter was located at Sage Top, while the tallest tree was located at Rehder Creek. The former result is rather surprising, considering that the tree was found on a south-facing aspect at the driest site. Absence of competitors, indicated by low stand densities at Sage Top, however, may have aided the 399-year-old tree.

Table 13:
Large Tree Maximum Age and Size Attributes

	ST	HC	CB	SB	RC
Oldest (years)	399	402	396	443	324
Youngest	125	122	122	82	91
Max height (ft)	63	76	75	74	98
Max dbh (in)	28.9	23.6	26.5	23.7	26.2

As Table 14 indicates, a majority of the large trees at each site showed signs of decadence in the form of crown or bole deformities. These deformities include broken, flattened, forked, or spiked tops and lean, sweep, or crook of the bole. Across all five sites, 62% of trees with dbh ≥ 15 in had one or more crown deformities and there was a moderate positive correlation between tree age and crown deformity. The most common crown deformity was a flat top (76% of trees with crown deformities). A flattened top is likely an expression of older trees that attained maximum height much earlier in life, but were unable to maintain apical dominance due to a combination of factors including: ice, wind, or biological agents, and lack of available water.

Table 14:
Percent of Large (≥ 15.0 in) Trees Displaying Damage by Site

Damage types	ST	HC	CB	SB	RC
Crown deformity	88	56	56	58	67
Bole deformity	58	54	54	52	29
External fire scar	14	43	33	28	30

Across all five sites, 22% of trees ≥ 15 in dbh had at least one external fire scar, while 9% had multiple fire scars. The frequency of readily detectable fire scars on large trees varied by site. Sage Top and Hay Coulee, the two driest sites, revealed the lowest (14%) and highest (43%) proportions of fire scarring, respectively. As a casual observation (no systematic measurement), I noticed no trees smaller than 12 in dbh with a fire scar or sign of scorching on the bole at any of the sites, possibly indicating the absence of recent fires at all sites. Fire scar abundance on large trees and presence of multiple scarring further supports the notion that these were equilibrium sites. However, a cross-dated fire history of the Bull Mountains would be required to validate this interpretation.

"Hidden" fire scars were found in increment cores from 10 trees ≥ 15.0 in; none were found in cores from trees < 15.0 in. The low abundance of hidden scars was likely a result of taking increment cores parallel to the slope, thus avoiding the commonly scarred uphill side of the tree. Chimney Butte and Silver Bullet had four trees each with hidden scars, and Hay Coulee and Rehder Creek each had one tree. No hidden scars were discovered on cores from trees sampled at Sage Top. The scarcity of detectable (external) and hidden fire scars at Sage Top further supports the interpretation that this site historically had lower tree density and corresponding low fuel loading and continuity than the other sites.

Table 15 displays the percent of large trees by vigor class and site. Although stand density at Sage Top was relatively low (Tables 8 and 10), this site had the lowest proportion (6.1%) of large trees with full (A) vigor, and none of the trees were of full vigor with an open-grown or "wolf" appearance (Thomson (1940) vigor class AA). Sage Top also had the greatest proportion (54.6%) of large live trees in the low (C) and weak (D) vigor classes combined, and the highest proportion of large dead trees. Although Silver Bullet had the highest proportion (7.4%) of weak vigor trees, it had relatively high proportions of large trees with full and medium (B) vigor. Relatively few of the large trees had weak vigor at any site, ranging from 2.9% at Chimney Butte to 6.1 % at Sage Top.

Abundance of full and medium vigor trees and scarcity of weak vigor trees across the five sites suggests that the stands are probably relatively healthy.

However, the relative abundance of low vigor trees at Sage Top may have been typical historically or might indicate potential decline at the site brought about by relatively recent droughty periods or grazing pressures. At the other four sites, small tree densities, which are likely high relative to historic levels, could cause declining vigor and reduced growth in older trees (Biondi *et al.* 1992, Biondi *et al.* 1994, Biondi 1996). Thus continued monitoring of large tree vigor and stand density would likely be beneficial for all five sites.

Table 15:
Percent of Large (≥ 15.0 in) Trees by Vigor Class and Location for the Bull Mountains Old-Growth Sites

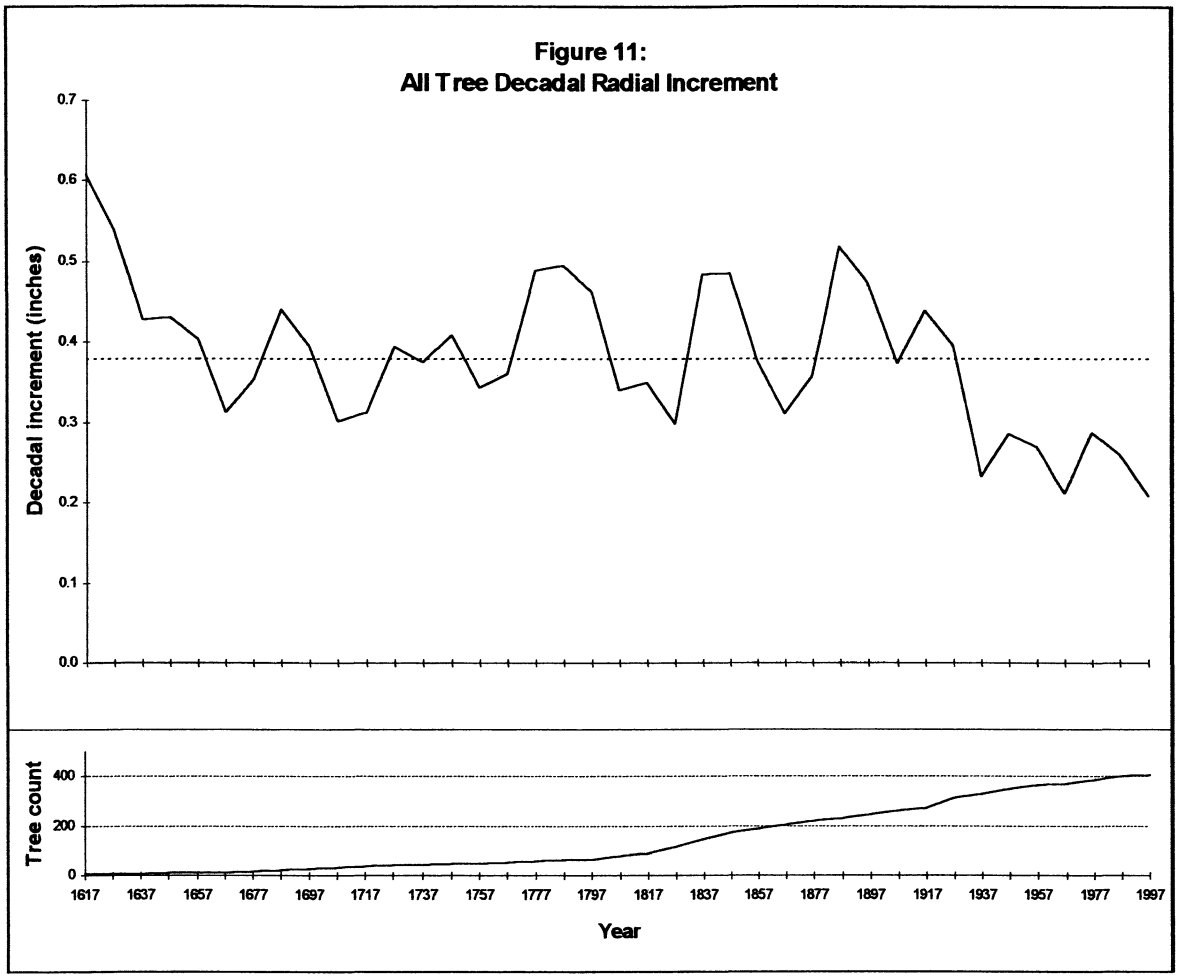
Vigor class	ST	HC	CB	SB	RC
AA*	0.0	4.2	9.6	3.7	12.2
A*	6.1	16.7	34.6	21.3	37.8
B*	39.4	50.0	31.7	45.4	32.4
C*	48.5	25.0	21.2	22.2	13.5
D*	6.1	4.2	2.9	7.4	4.1
X (Dead)**	25.0	14.3	12.6	14.3	11.9

* Computed as # in class/number of live, ** computed as # dead/total.

Growth Attributes

I hypothesized that tree growth in the Bull Mountains decreased since Euro-American settlement of the region. If such a decrease was detectable, several factors may have contributed: increased stand density resulting from fire suppression, climate change, and livestock grazing (Biondi *et al.* 1992, Biondi *et al.* 1994, Biondi 1996, Biondi 1999). However, analysis of large and small tree growth did not provide sufficiently strong evidence to conclude that tree growth in the Bull Mountains decreased since Euro-American settlement of the region.

Figures 11 - 14 show decadal radial increment plotted against time for all sites combined. The dashed line is the average decadal radial increment for the given tree population and time period. Decadal increment for all trees ranged between 0.209 in (decade ending 1997) and 0.608 in (decade 1608 to 1617). Although there was a weak negative trend in radial growth across the entire period, typical of the decrease in radial growth through time, there was a sustained decline in radial growth beginning during the decade 1888 to 1897. Between 1888 and 1997, eight of eleven decades revealed average radial increment values lower than the previous decade's, and the decade ending 1927 was the last with radial growth at or above the 300-year average. Figures 12 - 14 show similar patterns of radial increment decline of large (≥ 15.0 in) trees, small (< 15.0 in) trees, and large trees in the small tree period, respectively.



The mean (0.322 in) and range (0.218 in to 0.428 in) of average decadal radial increments for small trees (Figure 13) were smaller than the range (0.177 in to 0.554 in) and mean (0.357 in) of the large trees in the same time period (Figure 14), suggesting that radial growth in the past 200 years was slower and less variable among trees < 15.0 in than among trees ≥ 15.0 in.

Tree counts through time also are shown in Figures 11-14. The number of trees increased with time because of the sampling and measuring scheme. Any

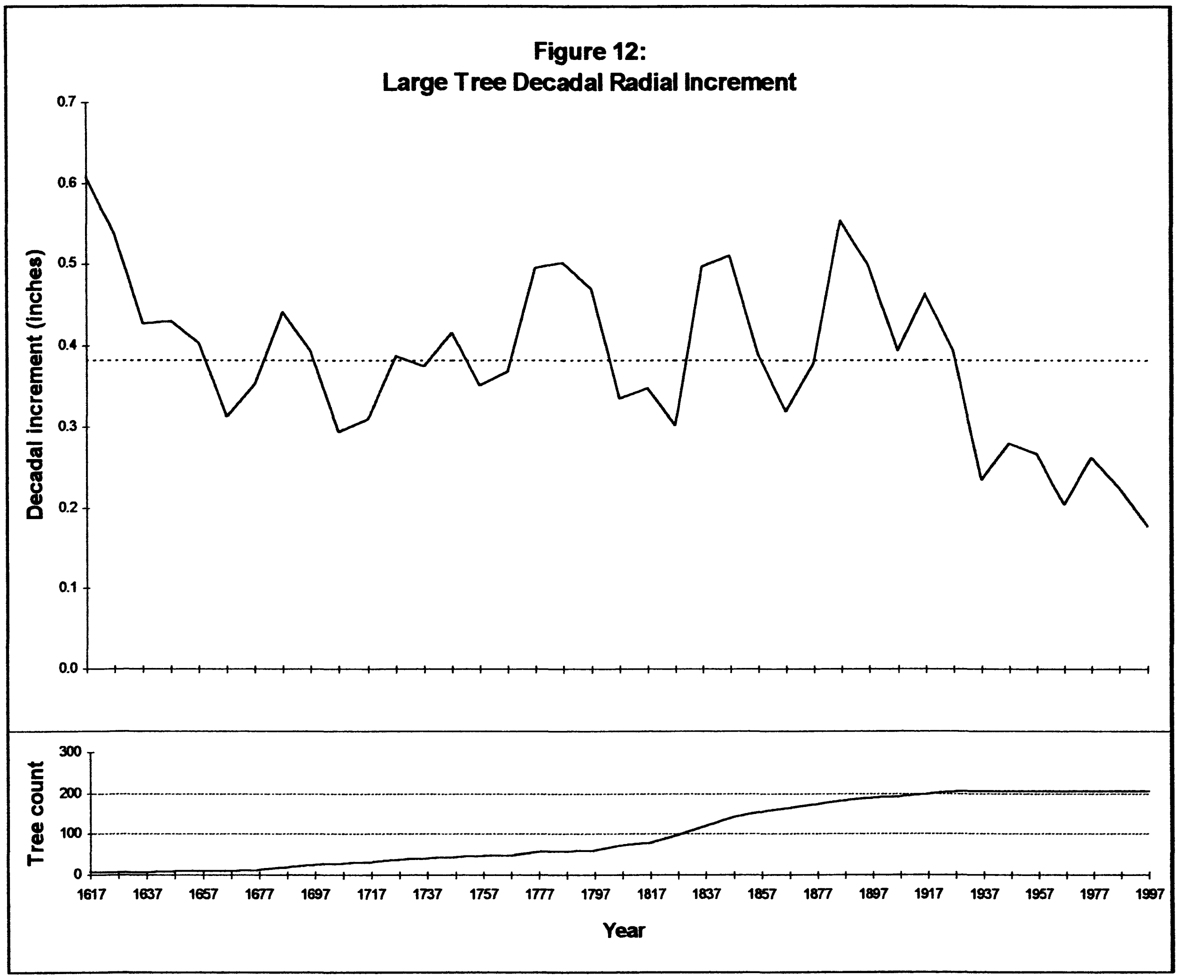


Figure 12:
Large Tree Decadal Radial Increment

tree that had growth measured in an earlier decade would have been counted in all later decades because only living trees were used in growth analysis. Thus, while ingrowth patterns can be detected by these plots, mortality patterns can not. Periodic increases in the rate at which the number of trees increases with time may indicate periods of successful regeneration, or a propensity for survival among trees that reached a height of 4.5 ft in that period. Increases in the slope of the number of trees vs. year are detectable from 1818 to 1847 among large trees

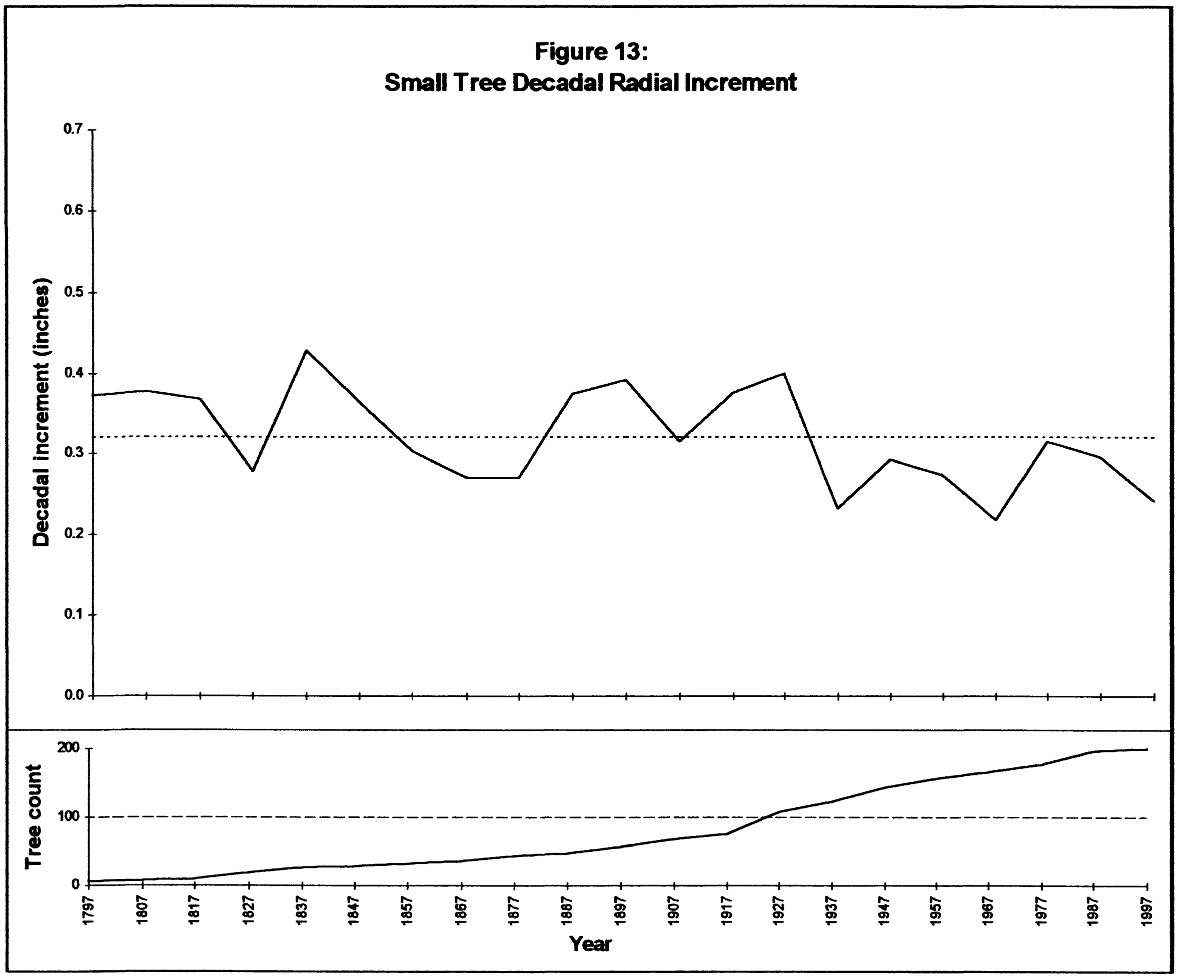
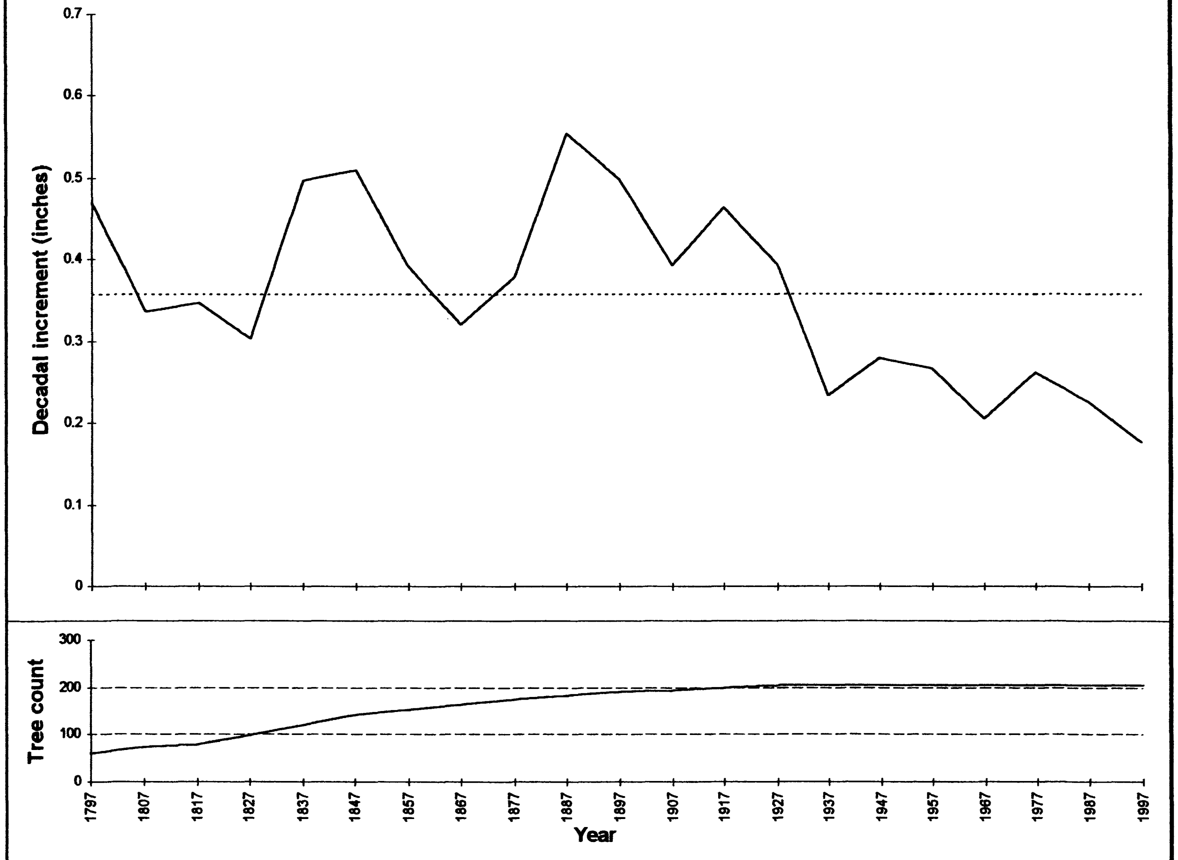


Figure 13:
Small Tree Decadal Radial Increment

(Figures 12 and 14), and among small trees from 1818 to 1837 and from 1918 to 1927 (Figure 13). These trends are also detectable when large and small trees are combined in the plot of all trees (Figure 11).

Trees 20 to 119 years old had significantly greater ($\alpha = 0.01$) average decadal radial growth during the past 120 years than trees ≥ 120 years had in the same period (Table 16), suggesting that trees established since Euro-American settlement of the Bull Mountains were growing faster than trees established

Figure 14:
Large Tree Decadal Radial Increment in Small Tree Period



before Euro-American settlement are currently growing. However, this is inconclusive since climate was not constant through time, and radial increment typically decreases with tree age (Fritts and Swetnam 1989, Jordan and Lockaby 1990).

Trees 20 to 119 years old had significantly smaller ($\alpha = 0.01$) average decadal radial growth during the past 120 years than trees ≥ 120 years had in the previous 120-year period, while trees ≥ 120 years also had significantly smaller (α = 0.01) average decadal radial growth in the past 120 years than they had in the previous 120-year period. This suggests that radial growth of trees in the Bull Mountains, regardless of age, was slower in the most recent 120 years (1878 - 1997) than in the previous 120-year period (1758 - 1877). This decreased growth may again be typical of radial increment changes through time, or may be due to the aforementioned factors associated with Euro-American settlement.

Table 16:
Average Decadal Radial Increment (in) by Time Period and Age Class

Current tree age	Post-settlement 12 decades (1878-1997)	Pre-settlement 12 decades (1758-1877)	Trees' first 12 decades
20 - 119 years	0.359	no data	0.359
≥ 120 years	0.294	0.391	0.420
≥ 200 years	0.179	0.328	0.387
≥ 300 years	0.161	0.262	0.364

The far-right column in Table 16 shows that trees 20 to 119 years old had significantly smaller (α = 0.01) average decadal radial growth in their first 12 decades than trees ≥ 120 years had during their first 12 decades. However, the average decadal radial growth of trees 20 to 119 years during their first 12 decades was not significantly different than growth during the first 12 decades of trees ≥ 300 years. These two results suggest that early radial growth of post-settlement trees was slower than early radial growth of pre-settlement trees, but that early radial growth of post-settlement trees is not outside the historical range of early radial growth rates for pre-settlement trees in the Bull Mountains.

Table 17 indicates that average decadal radial growth during the past 120 years was slowest in trees < 5 in and greatest in trees 10.0 in to 14.9 in. However, during the previous 120-year period, greatest average decadal radial growth occurred among trees (currently) ≥ 15.0 in. Average decadal radial growth during the past 120 years and during trees' first 12 decades was least in trees < 5.0 in and greatest in trees ≥ 15 in. The far right column in Table 17 indicates that current tree size is positively correlated with early radial growth.

Table 17:
Average Decadal Radial Increment (in) by Time Period and Size Class

Current tree size (dbh)	Post-settlement 12 decades (1878-1997)	Pre-settlement 12 decades (1758-1877)	Trees' first 12 decades
< 5.0″	0.189	no data	0.189
5.0″ - 9.9″	0.277	0.226	0.287
10.0″ - 14.9″	0.348	0.348	0.391
≥ 15.0″	0.326	0.403	0.457

Figures 15 - 18 show individual tree cumulative basal area increment (ft^2) for the first 30, 60, and 120 years of tree growth plotted against breast height pith date for all trees sampled for growth data. Decline in BAI for trees with breast height pith dates after 1877 cannot be detected in Figures 15 - 18. Decadal basal area increments ranged from 0.0162 ft^2 (decade ending 1617) to 0.0696 ft^2 (decade

Figure 15:
Scatter Plot of Cumulative Basal Area Increment (ft^2) for First 30, 60, and 120 Years of Tree Growth at Bull Mountains Old-Growth Ponderosa Pine Sites

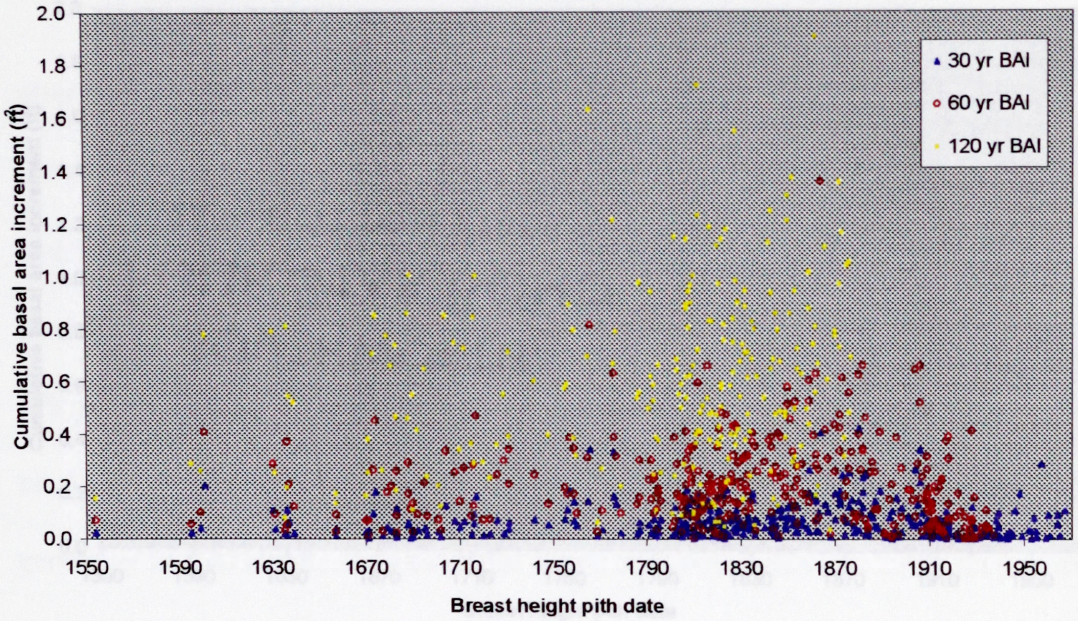


Figure 16:
Scatter Plot of Cumulative Basal Area Increment (ft^2) for First 30 Years of Tree Growth at Bull Mountains Old-Growth Sites

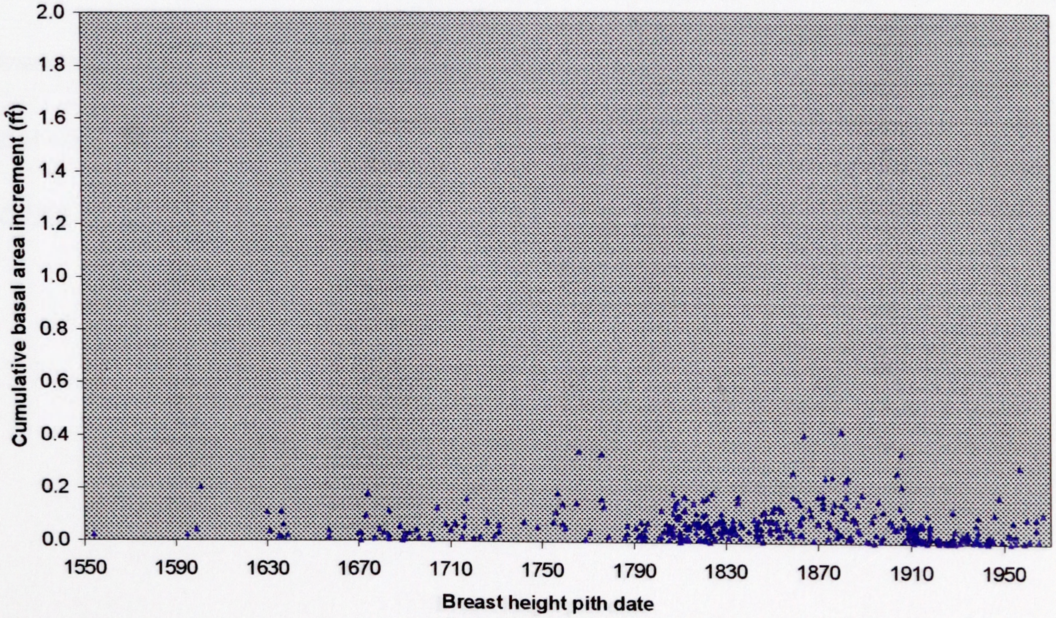


Figure 17:
Scatter Plot of Cumulative Basal Area Increment (ft^2) for First 60 Years of Tree Growth at Bull Mountains Old-Growth Sites

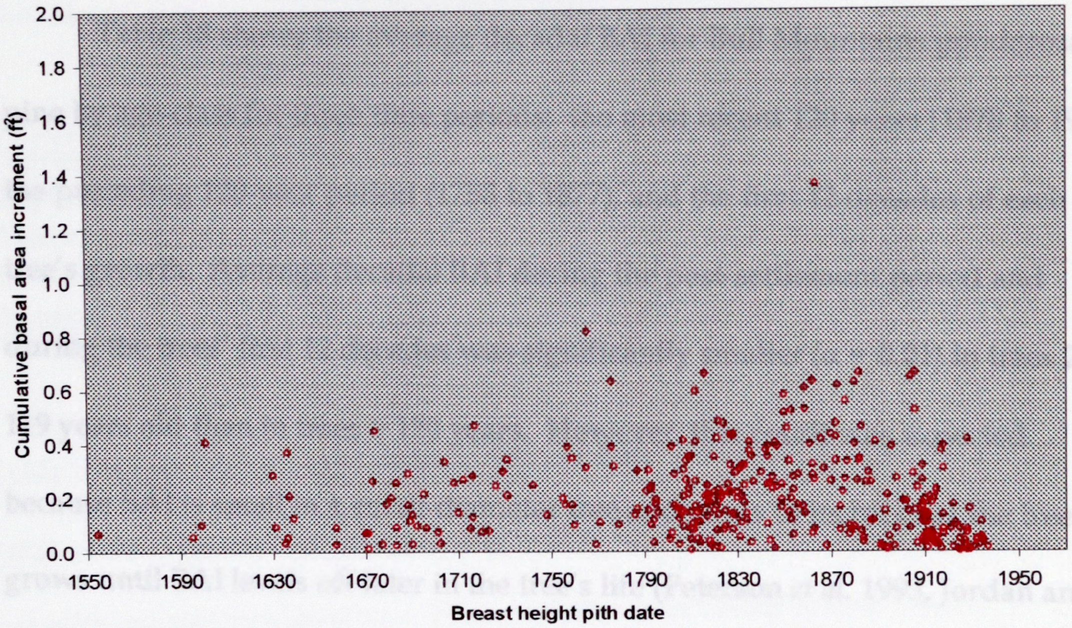
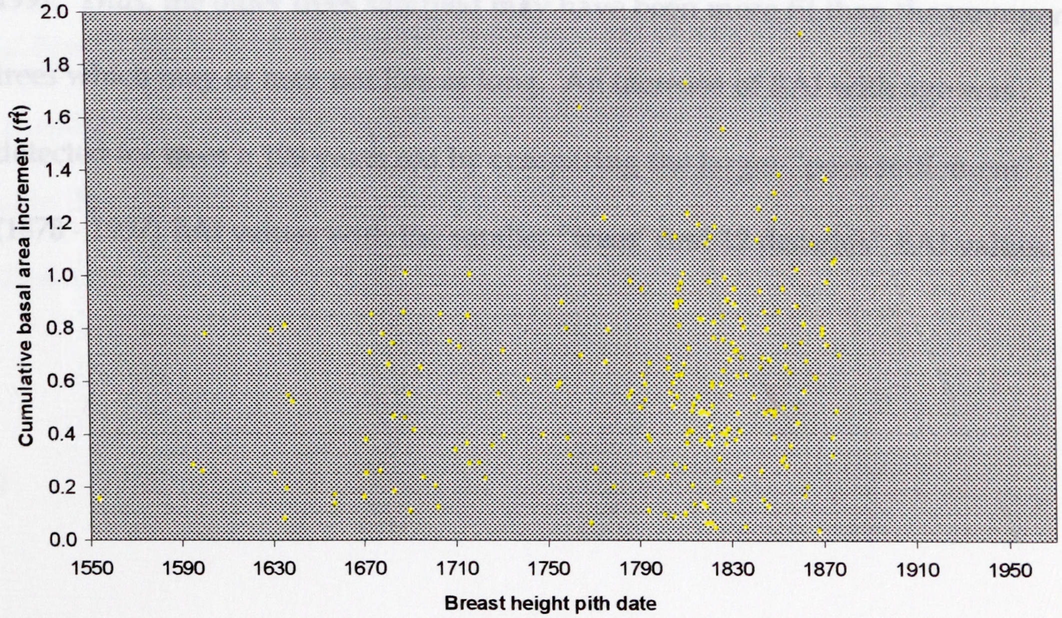


Figure 18:
Scatter Plot of Cumulative Basal Area Increment (ft^2) for First 120 Years of Tree Growth for Old-Growth Bull Mountain Sites



1908 to 1917). Between 1608 and 1997, the average decadal BAI for large and small trees combined was 0.0403 ft^2.

Table 18 shows the average decadal BAI for Bull Mountains ponderosa pine by age-class for three time periods: the most recent 120 years (1878 to 1997), the preceding 120-year period (1758 to 1877), and the first 12 decades of each tree's growth. Average decadal BAI during the post-settlement period and during the trees' first 12 decades was significantly smaller ($\alpha = 0.01$) in trees 20 to 119 years old than in trees ≥ 120 years. However, this result was expected because BAI is small in a small-diameter tree and tends to increase as the tree grows until BAI levels off later in the tree's life (Peterson *et al.* 1993, Jordan and Lockaby 1990). Interpretation of these growth results was also confounded by the fact that the only trees sampled were those which were alive and growing in 1997. Thus, the older trees sampled may have been more fit than the younger trees which may or may not live as long. An increase of BAI with age was detected for trees ≥ 120 years old by comparing the larger "post-settlement" (1878 - 1997) BAI values with the smaller "trees' first 12 decades" BAI values.

Table 18:
Average Decadal Basal Area Increment (ft^2) by Time Period and Age Class

Current tree age	Post-settlement 12 decades (1878-1997)	Pre-settlement 12 decades (1758-1877)	Trees' first 12 decades
20 - 69 years	0.0147	no data	0.0147
70 - 119 years	0.0316	no data	0.0316
≥ 120 years	0.0593	0.0410	0.0509
≥ 200 years	0.0499	0.0500	0.0428
≥ 300 years	0.0523	0.0553	0.0381

Table 19 shows the average decadal BAI for Bull Mountains ponderosa pine by size-class. The table unambiguously shows that BAI is positively correlated with current tree diameter. However, it is interesting to note that average decadal BAI for trees of all size-classes is significantly less ($\alpha = 0.01$) during the pre-settlement period (1758 to 1877) than the average decadal BAI for the trees' first 12 decades. A similar result can be seen among all size and age classes in radial growth (Tables 16 and 17), and among trees 20 to 119 years in BAI (Table 18). This may actually suggest a period of reduced growth during the pre-settlement period (1758 to 1877).

Table 19:
Average Decadal Basal Area Increment (ft^2) by Time Period and Size Class

Current tree size (dbh)	Post-settlement 12 decades (1878-1997)	Pre-settlement 12 decades (1758-1877)	Trees' first 12 decades
< 5.0"	0.0047	no data	0.0047
5.0" - 9.9"	0.0156	0.0053	0.0147
10.0" - 14.9"	0.0394	0.0225	0.0358
≥ 15.0"	0.0665	0.0450	0.0580

Periodic percent basal area growth (average *annual* BAI for 10-year period 1988 to 1997 expressed as a percent of total basal area in 1987) decreased exponentially with tree age (Figure 19). Values ranged between 0.97% and 32.09% for trees < 50 years, and 0.08% to 1.55% for trees > 200 years. Substantial differences in periodic percent basal area growth were detected among age classes, while size-class differences were much less abrupt (Table 20). Old-growth ponderosa pine in the Bull Mountains had periodic percent basal area growth rates between 0.3% (± 0.1%) and 0.6% (± 0.5%), whether the tree age was determined by ring-count (age ≥ 120 years) or estimated by size (dbh ≥ 15.0 in).

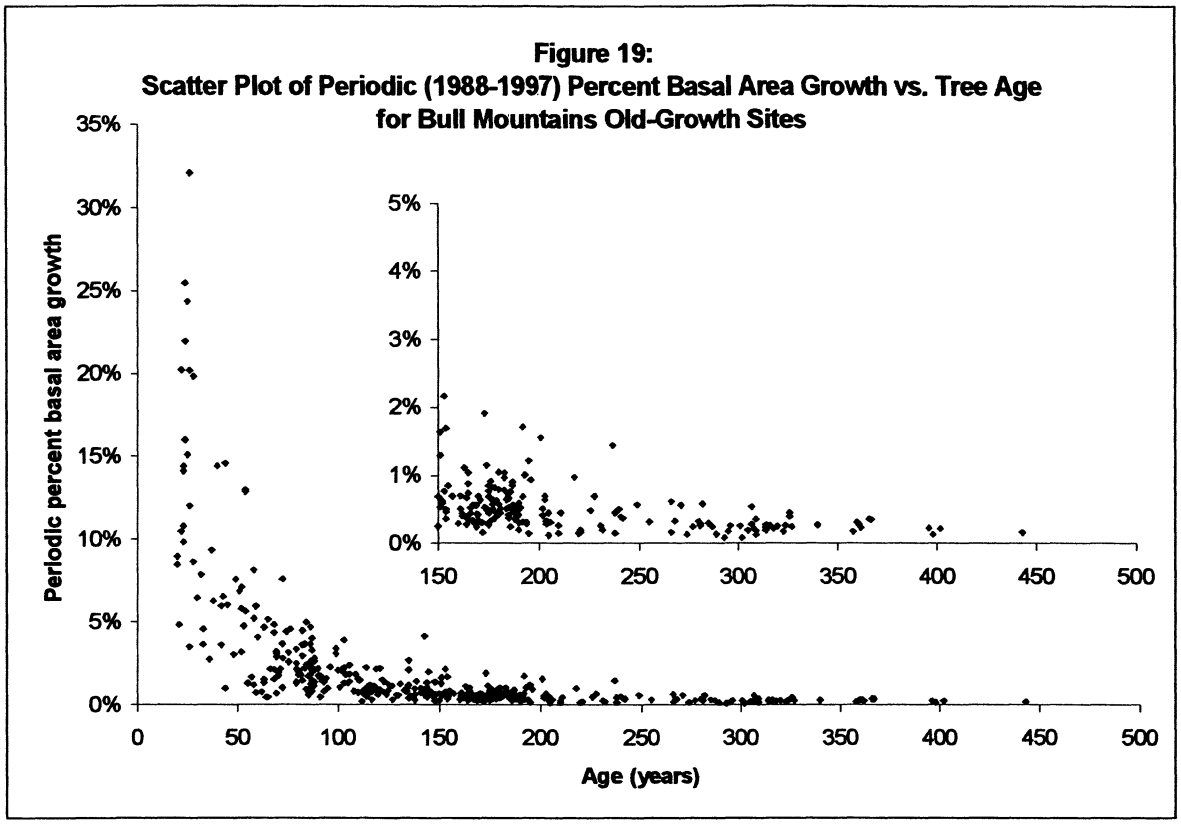


Figure 19:
Scatter Plot of Periodic (1988-1997) Percent Basal Area Growth vs. Tree Age for Bull Mountains Old-Growth Sites

Table 20:
Periodic (1988 - 1997) Percent Basal Area Growth (BAI/BA x 100%) by Age and Size Classes

Age class	Periodic percent basal area growth	Size class	Periodic percent basal area growth
20 - 69 years	7.78		
70 - 119 years	2.04	< 5.0"	6.85
≥ 120 years	0.60	5.0" - 9.9"	3.35
≥ 200 years	0.34	10.0" - 14.9"	1.75
≥ 300 years	0.25	≥ 15.0"	0.59

Spatial Analysis

Four spatial statistics were used to test the hypothesis that dispersion patterns of large trees at the Bull Mountains old-growth sites were not random. The outcomes and statistical significance of each outcome are shown in Table 21. Chimney Butte and Silver Bullet were the only sites where all four statistics revealed the same (clustered) dispersion of large trees. The patterns are significantly different than random at all sites according to the variance/mean ratio method. The aggregation index is the only other statistic that revealed a significant difference from random at any of the sites, namely Chimney Butte. Agreement and significance of statistics strongly suggests that the large trees at Chimney Butte, Silver Bullet, and Rehder Creek are clustered, while large trees at Sage Top are uniformly distributed.

Table 21:
Summary of Large Tree Dispersion Analysis Results by Statistic and Site

Spatial statistic	ST	HC	CB	SB	RC
G Empirical Distribution Function	N	C	C	C	C
Aggregation Index (R)	C	U	C*	C	U
Index of Nonrandomness (α)	U	U	C	C	C
Variance/ Mean Ratio	U**	C**	C**	C**	C**

C = clustered, U = Uniform, N = not tested, **significant at 0.05 level, *significant at 0.1 level.

Although the preponderance of statistics indicated clustering at all sites except Sage Top, the inconsistency of results did not provide a basis for concluding that clustering was an inherent characteristic of old-growth ponderosa pine. The dispersion of large trees may have resulted from differences in soil properties, topography, and other factors which influence site-specific or microsite tree regeneration and long-term survival patterns rather than from region-wide or species-specific factors.

Findings by White (1985) and Cooper (1960, 1961) suggest that old-growth ponderosa pine trees in the southwest are clustered. White (1985) noted strongly aggregated ($R = 0.58$) distribution of ponderosa pines ≥ 106 years old at a site in the Gus Pearson Natural Area near Flagstaff, Arizona. His various within-group tree ages, however, did not agree with Cooper's (1960, 1961) findings of even-aged clusters at three sites in the White Mountains of east central Arizona. White (1985) also notes that differences in precipitation patterns between his Flagstaff site and Cooper's White Mountain sites may account for differences in age structures and stem distribution patterns. Likewise, differences in timing and quantity of precipitation between central Montana and northern Arizona could partially account for differences in stem distribution patterns between this study and the Arizona studies.

Lack of agreement on dispersion patterns among spatial statistics in this study may have resulted from one or more of the following: different numbers of trees and different sizes (areas) of each site, different sample sizes inherent to the form of the statistic(s), edge effects, and truly random dispersion patterns of the large trees. More thorough explanations of these sources of error and results of the individual tests are provided below.

G Empirical Distribution Function

The point pattern maps of four sites (Hay Coulee, Chimney Butte, Silver Bullet, and Rehder Creek) and the corresponding G empirical distribution function (G EDF) plots with and without complete spatial randomness (CSR) simulation envelopes are shown in Figures 20 through 23. The point pattern maps and G EDF plots seem to indicate nearly random point patterns with the possibility of some slight clustering. The G EDF plots show the shapes of the G EDF as quite angular with nearest neighbor distances spanning a relatively large range of distances, indicating relatively random large tree dispersion. Approximately 50% of large trees (dbh ≥ 15.0 in) at Silver Bullet had nearest neighbor distances ≤ 20 ft, while at Hay Coulee only 20% of large trees had nearest neighbors ≤ 20 ft.. The G EDF plots with CSR simulation envelopes show the function passing through the upper boundaries of the simulation envelopes, indicating clustered point patterns. However, comparing the severity of the departures from the CSR envelopes in the cluster simulations (Figure 3) to the mild departures in the site plots (Figure 20 through Figure 23), the sites showed only weak evidence of clustered dispersion of large trees.

Figure 20:
Results of Large Tree Dispersion Analysis at Chimney Butte
Using G Empirical Distribution Function

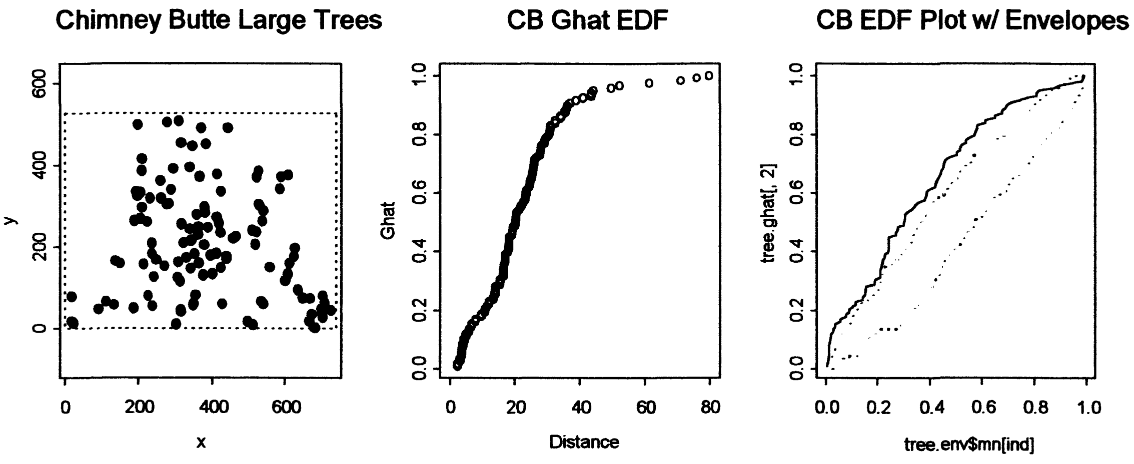


Figure 21:
Results of Large Tree Dispersion Analysis at Silver Bullet
Using G Empirical Distribution Function

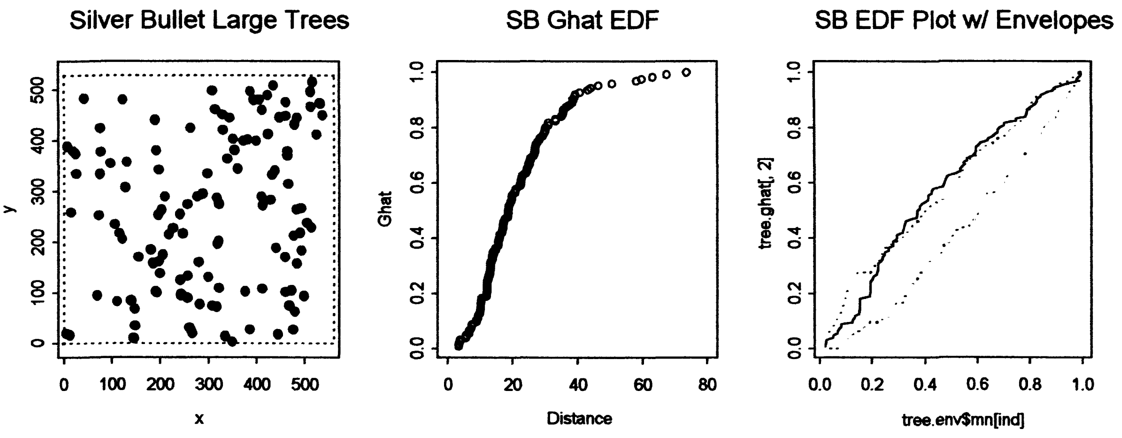


Figure 22:
Results of Large Tree Dispersion Analysis at Rehder Creek
Using G Empirical Distribution Function

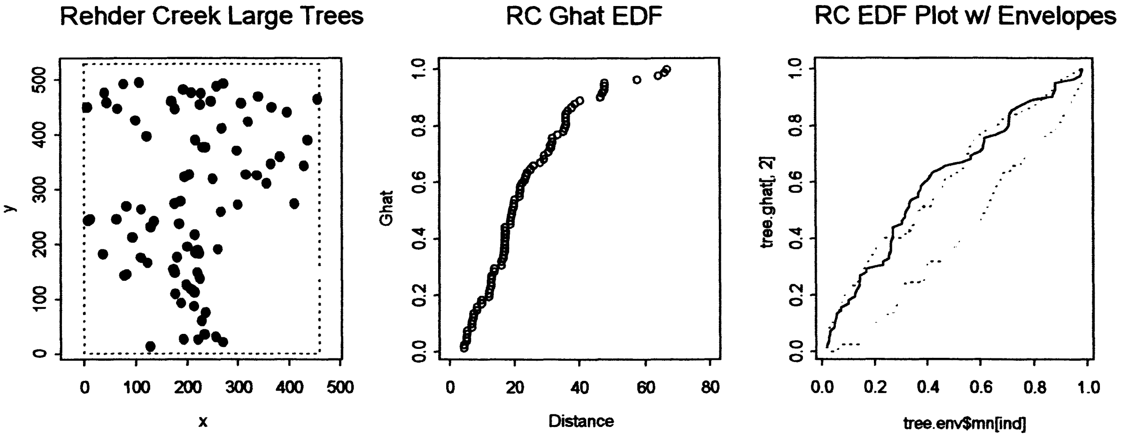
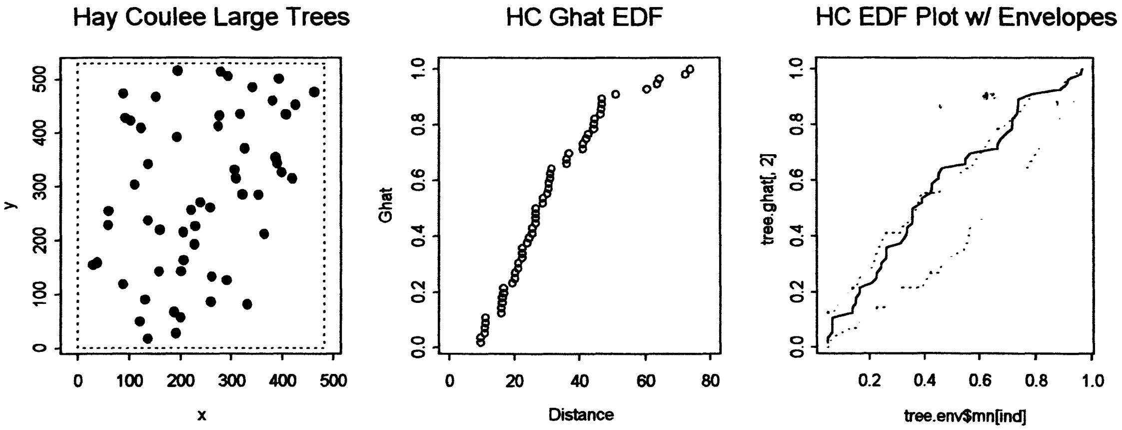


Figure 23:
Results of Large Tree Dispersion Analysis at Hay Coulee
Using G Empirical Distribution Function



Aggregation Index

The aggregation index (R) values and calculated z (z_{calc}) values for all five sites are shown in Table 22. Although R < 1 for Sage Top, Chimney Butte, and Silver Bullet and R > 1 for Rehder Creek and Hay Coulee, the z_{calc} values indicated that none of the sites had a point pattern significantly different from complete spatial randomness (CSR) at the 95% level. For all sites, the absolute z_{calc} value was less than the z = 1.96 critical value needed to reject the null hypothesis of no difference from CSR at the 95% level. However, at Chimney Butte, the absolute z_{calc} value was greater than the z = 1.65 critical value needed to reject the null hypothesis of no difference from CSR at the 90% level, suggesting Chimney Butte may have had a clustered dispersion of large trees.

Table 22:
Results of Large Tree Dispersion Analysis Using Aggregation Index (R)

	ST	HC	CB	SB	RC
A (ft^2)	220374.0	184852.8	269992.8	246694.8	170438.4
N	42	54	115	123	79
λ	0.000191	0.000292	0.000426	0.000499	0.000464
d_{exp}	36.2181	29.2541	24.2269	22.3922	23.2242
d_{obs}	33.0296	31.4552	22.1966	22.0150	23.6180
R	0.91	1.08	0.92	0.98	1.02
z_{calc}	-1.09	1.06	-1.72*	-0.36	0.29

A = area, N = number of trees, λ = density (N/A), d_{exp} = expected average nearest neighbor distance, d_{obs} = observed average nearest neighbor distance, R = ratio of d_{obs} to d_{exp}, z_{calc} = calculated z statistic, ** significant at 0.05 level, * significant at 0.1 level.

The "uniform" results of the aggregation index calculations for Rehder Creek and Hay Coulee disagreed with the "clustered" G EDF and variance/ mean ratio results (Table 21). This may have been due to the relatively small number of trees at these two sites or edge effects. As Table 22 indicates, Sage Top, Rehder Creek, and Hay Coulee had relatively few trees. The aggregation index values should prove to be accurate for N's greater than six (Ripley 1981, Boots and Getis 1988), but the z_{calc}-statistic used to test the significance of R may not have been appropriate since the standard error of the z_{calc}-statistic depends on N being large (Graham 1999). Since the numbers of trees in the patterns at Sage Top, Rehder Creek, and Hay Coulee were substantially less than 100, small N is a possible cause of the aggregation index's inability to detect differences from CSR at these sites.

Both Chimney Butte and Silver Bullet had N's greater than 100, thus the aggregation index and z_{calc}-statistic should provide accurate assessments of the dispersion of large trees at the sites. The fact that the other three spatial statistics agreed (though not all at significant levels) suggests that these two sites did indeed exhibit clustering of large trees.

Edge effects are an issue when examining bounded patterns because the aggregation index equations used by Clark and Evans (1954) relate to the nearest neighbor properties of an infinite or unbounded CSR pattern (Boots and Getis 1988). The CSR envelopes used to test the G EDF's "consider{ed}" edge effects (Kaluzny 1998), but no explanation of how the edge effects were considered was given in the S-Plus Manual. According to Boots and Getis (1988), four methods can be used to compensate for edge effects: 1) if the area is a rectangle, convert it to a torus; 2) ignore all points in the pattern that are closer to the boundary than they are to any point in the pattern; 3) delimit the study area as a smaller portion of the entire point pattern or create a "buffer" zone; or 4) if the area is not highly irregular, then add a "correction factor" to the equations used to calculate d_{exp} and variance of d_{obs}.

A modification of the first edge effect compensation method was employed in this study. Rather than connecting opposing sides of the same transect--as with a torus (Boots and Getis 1988), parallel sides of neighboring transects were connected. Since the number of trees in each transect at each site was relatively small and the objective was to make inference on the dispersion of large trees at each site (not each transect), the data for the four transects at each site were combined and the regions of no data between the transects were ignored. The assumption was made that the tree dispersions within and between transects were products of biotic and abiotic factors which operated similarly within and between transects.

Index of Nonrandomness

As Table 23 indicates, none of the sites possessed a large tree dispersion pattern significantly different than random at either the 95% or 90% levels, using

Pielou's (1959) index of nonrandomness. Index values also inconsistently agree with other dispersion analysis results (Table 21). Chimney Butte and Silver Bullet are the only sites where the index of nonrandomness agreed with all other methods on the (clustered) dispersion pattern of the large trees. The Sage Top (uniform) index of nonrandomness result disagreed with the aggregation index result, but agreed with the variance/mean ratio result. Index of nonrandomness results agreed with the aggregation index result at Hay Coulee, although these two results disagreed with the G EDF and variance/mean ratio results.

Table 23:
Results of Large Tree Dispersion Analysis Using Index of Nonrandomness

	ST	HC	CB	SB	RC
Number of distances	13	11	16	15	10
Mean of square distances	1463.4	705.5	956.3	878.9	753.3
Density (λ)	0.000191	0.000292	0.000426	0.000499	0.000464
α	0.878	0.647	1.280	1.378	1.098

α = index of nonrandomness, ** significant at 0.05 level, * significant at 0.1 level.

The likely cause of the index of nonrandomness' insignificant results was the small sample size (all N's < 20) used in the calculation of the statistic at each site. The small samples resulted from the method used to stem map the trees. A possible way to overcome the sample size problem would be to use a computer to generate 10 to 20 random points within each transect, find the distance from each point to the nearest large tree, then calculate α.

Variance/ Mean Ratio

The variance/mean ratio method produced the most significant findings at the most sites (Tables 21 and 24). The variance/mean ratio is scale-sensitive but insensitive to the spatial arrangement of the quadrats (Boots and Getis 1988). Thus, if used as the only measure of dispersion, the statistic should be calculated from quadrats of different sizes and at each scale the quadrats ought to be tested for spatial autocorrelation.

Table 24:
Results of Variance/ Mean Ratio Method at Various Quadrat Sizes

Quadrat Size	ST	HC	CB	SB	RC
33' x 33'	1.13	0.87	1.09	1.04	1.02
66' x 66'	1.00	0.82	1.51**	1.13*	1.29**
132' x 132'	0.63**	1.62**	1.96**	2.21**	1.45**

** significant at 0.05 level, * significant at 0.1 level.

Table 24 shows the large tree dispersion pattern results of the variance/ mean ratio method at three scales. A rule of thumb for determining the appropriate quadrat size is twice the area per point, or $Q = \sqrt{(2A/N)}$; where A is area and N is the number of points (i.e., large trees), Q equals the length of a side of a square quadrat (Boots and Getis 1988). Using A and N from Table 22, appropriate quadrat sizes ranged between 64 ft at densely stocked Silver Bullet and Rehder Creek sites and 102 ft at sparsely stocked Sage Top. However, 33 ft, 66 ft, and 132 ft quadrats were used at all sites because the 132 ft wide strip plots readily allowed changing quadrat sizes for these scales.

Using the small quadrats, 33 ft on a side, the large trees at each site do not have dispersion patterns significantly different than CSR. At this scale, each site was divided into 152 to 240 quadrats. Thus the lack of significant difference from CSR was not due to small sample size. Rather, the quadrat size was likely too small and any clusters that existed may have been subdivided, producing a bias toward CSR (Boots and Getis 1988).

The intermediate quadrat size (66 ft x 66 ft) revealed statistically significant clustering of large trees at three sites: Chimney Butte ($\alpha = 0.05$), Silver Bullet ($\alpha = 0.1$), and Rehder Creek ($\alpha = 0.05$). Sage Top and Hay Coulee did not have dispersion patterns significantly different than CSR at this scale, and sample sizes at these sites were relatively large, 38 and 48 quadrats, respectively. However, the twice the area per point rule of thumb suggested quadrat sizes of 102 ft and 82 ft for Sage Top and Hay Coulee respectively. Thus the lack of significant difference from randomness at Sage Top and Hay Coulee was probably a function of quadrat size and tree dispersion.

Analysis using the large quadrats (132 ft x 132 ft) revealed a statistically significant uniform dispersion of large trees at Sage Top ($\alpha = 0.05$), which agreed with the index of nonrandomness result, supporting the conclusion that Sage Top had uniformly distributed large trees. The uniform pattern at Sage Top may have been due to historic competition for resources on the dry site (Barbour *et al.*

1999, Dale 1999), or may have resulted from over-sized quadrats which can bias the variance/mean ratio result toward a uniform pattern (Boots and Getis 1988).

Significantly clustered dispersion patterns at the remaining four sites (α = 0.05) agreed with G EDF results. Agreement among the variance/mean ratio results at the two larger scales and the G EDF results strengthens the conclusion that Chimney Butte, Silver Bullet, and Rehder Creek did exhibit clustered dispersion patterns of large trees. Clustered patterns can result from environmental heterogeneity so that plants of the same species are found clumped together in favorable areas (Dale 1999). Clustering at the Bull Mountains sites may have resulted from topographic and soil conditions that favored seedling establishment, provided available water, and/or increased survival probability during fire events. Moir (1992) and Oliver and Larson (1996) note that tree survival and spatial distribution are not random, but functions of age, site conditions, and stand (disturbance) history. Further study of tree clusters and open spaces surrounding the clusters could provide greater insight into the scale of and mechanisms responsible for ponderosa pine dispersion patterns in the Bull Mountains.

Conclusion

The purpose of this thesis was to fill the gap in knowledge that land managers and researchers had about old-growth ponderosa pine in the Bull Mountains of Musselshell County, Montana. The objectives were to provide background ecological information about ponderosa pine in central Montana, and to describe and quantify site, stand, and individual tree features of old-growth ponderosa pine on Montana DNRC lands.

Results indicated that ponderosa pine was the climax species and that old growth occurred as a component of uneven-aged forested areas on various slopes and aspects, often along drainage features. Old-growth groves in this study ranged between 5 acres and 16 acres. Tree densities ranged between 99 tpa and 166 tpa, with 6.8 to 17.7 tpa ≥ 15 in. Basal area densities ranged from 71 ft^2 to 99 ft^2 per acre, with 11.5 ft^2 to 30.6 ft^2 per acre in trees ≥ 15 in. Regeneration at the sites was highly variable, ranging from 4 to 2056 seedlings per acre and 54 to 656 saplings per acre. Between 1.6 and 3.2 large snags (≥ 15 in) per acre were also found in each stand. Ponderosa pine in the Bull Mountains attained ages in excess of 400 years, with average heights of old-growth trees ranging from 45 ft to 63 ft, and diameters approaching 30 in. Growth rates of individual old-growth trees ranged between 0.32 in and 0.59 in of diameter per decade, and 0.0499 ft^2 to 0.0593 ft^2 of basal area per decade. Tree growth rates were not found to be significantly slower since Euro-American settlement of the region, although a period of reduced growth was noted prior to settlement. Spatial statistics indicated that large trees occurred in clustered patterns at four sites and in a uniform pattern at one site. Spatial and age distributions of trees, evidence of decadence and fire-scars, and relatively low density of large trees suggested that the five Bull Mountains sites supported old growth in uneven-aged stands that were historically maintained in equilibrium with minor disturbances, particularly low-intensity surface fires.

Future old-growth studies in the region might concentrate on size and age structure of tree clusters to determine if they are even- or uneven-aged, while investigation of regional climate history would greatly strengthen knowledge of current and historic tree growth and stand density changes. A cross-dated fire history of the Bull Mountains would greatly benefit our understanding of the spatial and temporal distributions of disturbances in the region, and is needed for development of an ecologically sound definition of old growth. This knowledge would further the manager's ability to develop or maintain old-growth stand components or structures.

The findings presented in this thesis are a step toward better understanding of ecology, structure, and processes of old-growth ponderosa pine in central Montana. However, the continued existence of old growth in the Bull Mountains is at risk from catastrophic fire and removal of old trees through logging. Uncut old-growth sites in the Bull Mountains are quite scarce; two of the five old-growth sites in this study were logged since 1998. Diameter-limit harvesting will not maintain the quantity, quality, or spatial distribution of large trees characteristic of uncut old-growth sites, and does not reduce small tree densities sufficiently to protect potential old-growth sites from conflagration.

Therefore, I suggest that DNRC foresters do the following: 1) revise old-growth definitions according to ecologically sound criteria that account for regional climate and vegetation, forest growth stage, and disturbance history; 2) protect the three remaining uncut old-growth sites; 3) re-measure the two harvested old-growth sites to compare old-growth attributes pre- and post-harvest; and 4) compare attributes measured in this study to cut and uncut stand histories and inventories to identify other old-growth sites. Protection of Rehder Creek and Hay Coulee may require pre-commercial thinning to reduce small tree densities for the purpose of reducing stress on larger, older trees and removing the "green ladder" which allows surface fires to reach large tree crowns. Protection of Sage Top may require grazing to be temporarily reduced on the site to allow regeneration and protect the soil.

Maintaining old growth in the Bull Mountains would appear prudent given the 1996 State Forest Land Management Plan and the ecological uncertainty associated with long-term forest management. With continued interest in old-growth conservation and development of new knowledge and understanding through research, foresters should be able to manage central Montana's ponderosa pine forests to generate revenue for the school trust and provide the various old-growth resources and values that the public demands.

Appendix A

Table A1:
Vigor classification system used in Bull Mountains old-growth study

Vigor class	Percent live crown	Crown position	Crown width	Needle appearance
AA "wolf"	> 70%	isolated	average or wider	long, healthy, full
A "full"	50% - 70%	dominant	average or wider	long, healthy, full
B "medium"	30% - 50%	codominate/ dominate	average	average length, healthy, full
C "low"	20% - 30%	intermediate	average or slightly less	average to short, not healthy, sparse
D "weak"	< 20%	suppressed	below average	short, not healthy, sparse

Classification system adapted from Keen 1943, Thomson 1940, and Hornibrook 1939. Used for large (dbh ≥ 15.0″) trees estimated to be ≥ 120 years old.

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