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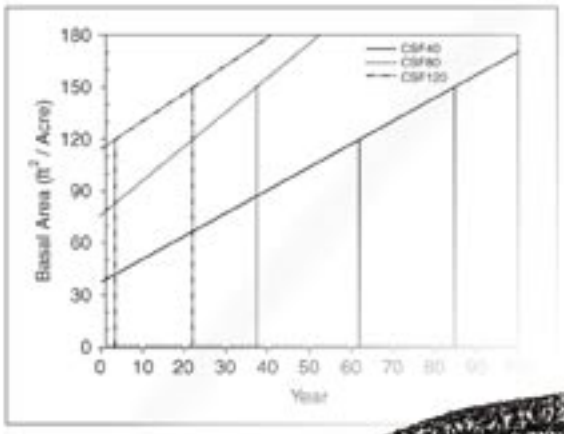
Growth of Lodgepole Pine Stands and Its Relation to Mountain Pine Beetle Susceptibility

S. A. Mata, J. M. Schmid, and W. K. Olsen









Susceptibility ratings for each GSL

Location/GSL	At Installation	After Marking	After Remeasurement
Brush Creek (WY)	Moderate	Moderate	Moderate
GSL40	Moderate	Moderate	Moderate
GSL60	Moderate	Moderate	Moderate
GSL80	Moderate	Moderate	Moderate
GSL120	Moderate	Moderate	Moderate
Control	Moderate	Moderate	Moderate
Colorado State Forest (CO)			
GSL40	Moderate	High	High
GSL80	High	High	High
GSL120	Moderate	High	High
Control	Moderate	Moderate	High

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Abstract

Periodic diameter and basal area growth were determined for partially cut stands of lodgepole pine at five locations over approximately 10 year periods. After cutting, average diameters in the partially cut plots generally increased by 0.8 inches or more, while average diameter in the uncut controls increased by 0.6 inches or less. Diameter growth in the partially cut plots was generally significantly greater than diameter growth in the controls. Individual tree growth is discussed in relation to potential susceptibility to mountain pine beetle infestation. Basal area decreased in three of the four GSL (growing stock level) 40 stands because of windthrow. Basal area generally increased ≥1.0 ft^2/acre/year in partially cut plots except in the GSL 40 stands with substantial windthrow and one GSL 100 with an Armillaria infection pocket. Basal area increases in the control plots ranged from 0.2 to 1.1 ft^2/acre/year, although the one control with a BA growth rate of 1.1 ft^2/acre/year had a relatively low initial BA. Data from the stands are employed in the susceptibility rating methods of Amman et al. (1977), Shore and Safranyik (1992), and Anhold et al. (1996) to determine stand susceptibility and the results discussed in terms of general applicability of these methods to partially cut stands. Basal area growth is used to estimate the length of time required for various stand densities to reach specific susceptibility thresholds for mountain pine beetle infestation. Several of the GSL 40 stands are not projected to reach the susceptibility thresholds in <100 years because of windthrow. Barring mortality >1%, GSL 80 stands are estimated to reach the basal area threshold of 120 ft^2 per acre in <25 years. GSL 120 stands, essentially at the basal area 120 threshold, are generally projected to reach the basal area threshold of 150 ft^2 per acre in <35 years.

Keywords: Lodgepole pine, basal area growth, diameter growth, mountain pine beetle, stocking levels

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Natural Resources Research Center
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Growth of Lodgepole Pine Stands and Its Relation to Mountain Pine Beetle Susceptibility

S.A. Mata[1], J.M. Schmid[1], and W.K. Olsen[2]

Introduction

Knowledge of tree growth under various stand and site conditions is essential for managing stands of lodgepole pine (LP), *Pinus contorta* Douglas. Such knowledge is necessary for developing growth and yield models that are used to predict future outcomes for different silvicultural prescriptions. Knowledge of tree growth and stand conditions is also useful for predicting when unmanaged stands and partially cut stands may become susceptible to infestation by the mountain pine beetle (MPB), *Dendroctonus ponderosae* Hopkins.

Susceptibility of LP stands to MPB attack has been defined by Shore and Safranyik (1992) as "the inherent characteristics or qualities of a stand of trees that affect its likelihood of attack or damage by a MPB population." Their definition conceptualizes susceptibility in terms of the probability of MPB infestation and not in terms of subsequent tree mortality as some prior authors assumed in their susceptibility rating methods. Although the Shore and Safranyik susceptibility-rating method provides a long-term index of potential basal area loss in the event of a MPB infestation (Shore et al. 2000), its primary function is the probability of MPB infestation. This paper discusses hazard rating methods wherein susceptibility may have been defined with some measure of tree mortality, but it follows Shore and Safranyik's 1992 definition for susceptibility without the connotations of subsequent mortality, i.e., just the probability of MPB infestation.

Methods for estimating the susceptibility of unmanaged LP stands to MPB infestation have been developed by Amman et al. (1977), Anhold et al. (1996), Berryman (1978), Mahoney (1978), and Shore and Safranyik (1992) among others. Most of the various methods are based on stand characteristics (Bentz et al. 1993) such as diameter at breast height (DBH), stand density expressed in terms of basal area (BA) or number of stems per ha, age in years, percentage of susceptible pine BA, a periodic growth ratio, or a crown competition factor as they interact with the combined influence of elevation, latitude, and longitude for the particular stand. More importantly, of the numerous methods developed for determining susceptibility, nearly all are primarily designed for unmanaged stands, are not designed to rate managed stands, or have limitations if used to determine when managed stands may become susceptible.

Three methods previously or currently used to estimate the susceptibility of LP stands have been developed by Amman et al. (1977), Shore and Safranyik (1992), and Anhold et al. (1996). In the Amman et al. (1977) method, susceptibility of lodgepole pine stands is a function of elevation and latitude, average tree age, and average DBH. Susceptibility is greatest when: elevation is below 9500 ft, latitude is less than 49^0, average age >80 years, and average DBH >8 inches (Amman et al. 1977). In the Shore and Safranyik (1992) method, susceptibility is a function of the percentage of susceptible pine basal area, age of the stand in years, density of the stand in terms of stems per ha, and location (a combination of longitude, latitude, and elevation). Susceptibility is greatest when: the stand contains a high percentage of pine with diameters ≥15 cm DBH (6 inches), the average age of dominant trees >80 years, the number of stems per ha is between 750 and 1000 (304 and 405 trees per acre, respectively), and, generally, elevation, latitude, and longitude are at the lower values for their respective ranges. In the Anhold et al. (1996) method, susceptibility is defined by the

[1]Forestry Technician and Forest Entomologist (retired), respectively, Rocky Mountain Research Station, Fort Collins, Colorado 80526.

[2]Forestry Consultant, W.K. Olsen & Associates, L.L.C., Bellvue, Colorado 80512.

relative density of the stand compared to maximum stand density as expressed by the stand density index (SDI). Stands with densities of 20% to 35% of the maximum SDI and a quadratic mean diameter >8" define a "zone" of high susceptibility. Stands with densities of <20% and >35% of maximum SDI, or a quadratic mean diameter <8 inches are assumed to have low susceptibility. More pertinent for comparison to our data, the "zone" of high susceptibility equivocates to specific numbers of trees per acre for quadratic mean diameters >8 inches with the lower (20% SDI) and upper (35% SDI) limits of the "zone" decreasing as diameter increases.

This paper reports on the diameter and basal area growth of partially cut and uncut LP stands at five locations in southern Wyoming and northern Colorado. The stand conditions of each plot before and after partial cutting are evaluated in terms of the susceptibility rating criteria of Amman et al. (1977), Shore and Safranyik (1992), and Anhold et al. (1996) to estimate their initial and future susceptibility. The stand conditions and tree growth are also used in straight-line projections and a growth and yield model to estimate when the stands might enter susceptibility thresholds as determined for the MPB in ponderosa pine, *P. ponderosa* Lawson. The results are discussed in relation to the future susceptibility of these stands to MPB infestations, and their implications for management.

Methods

During a study of the relationship between stand density and MPB-caused tree mortality, sets of growing stock level (GSL)[3] plots were installed in susceptible-size LP stands in southern Wyoming and northern Colorado between 1984 and 1987. Each set typically consisted of four 1-ha (2.47-acre) plots; 3 plots partially cut to different GSLs and the fourth plot left uncut to serve as a control. Occasionally, an additional 1-ha (2.47-acre) plot was installed and partially cut when stand conditions allowed.

[3]Growing stock level (GSL) is defined as the residual square feet of BA when the average diameter of the stand is ≥10 inches (Alexander and Edminster 1981). When the average diameter is <10 inches, BA is numerically less than GSL. While BA is more commonly used and preferrable than GSL, the plots were installed under the GSL concept so the results are reported as such. Further, statements regarding specific GSL levels become awkward when reported in BA equivalents because a range of BAs must be used if the average diameter is less than 10 inches.

Leave trees within cut plots were selected on the basis of DBH, spacing, tree form, crown development, visually apparent good health, and species. Tree selection emphasized leaving the best and largest LP as evenly spaced as possible. Other tree species such as aspen, *Populus tremuloides* Michaux, were marked to be cut. The process of tree selection attempted to leave the GSL within ±1 of the designated level (i.e., a GSL 80 stand would be between 79 and 81).

When installed, the central 0.5 ha (1.24 acres) of each plot were designated as the central inventory plot (CIP). DBH was measured on all trees within the CIP. Tree diameters and information on crown form, defects, the presence or absence of MPB attacks, and diseases were recorded. Metal tags were placed at about breast height on the designated leave trees in the CIP to facilitate record keeping in regard to MPB infestation and the determination of individual tree growth in subsequent years. Trees in the CIP provided the growth information and were the basis for statements regarding diameter and BA growth on the 1-ha (2.47-acre) plots.

Trees were also examined for the presence of MPB attacks and physical damage during surveys subsequent to cutting. Trees with MPB attacks were classified as "successfully attacked" or "pitchout" (a pitchout is a tree that has external evidence of MPB attacks but survives the attacks). Trees were examined the following year to verify the classification.

Sets of plots were installed on the Medicine Bow National Forest in southern Wyoming and on the Colorado State Forest in northern Colorado. Two sets of plots (Divide Peak [DPEAK]) and North Savery [NSAV]) were installed about 24 miles southwest of Saratoga, WY and one set (Brush Creek [BCRK]) was installed about 21 miles southeast of Saratoga. Two sets of plots were installed near Gould, CO: one set (Colorado State Forest [CSF]) about 5 miles northeast of Gould and one set (KOA) 1 mile northwest of Gould. Two of the CSF plots were superimposed on stands that had been partially cut prior to our establishment of the plots. Additional plot information with respect to dates of installation, cutting, and remeasurement, elevation, site index, etc., is presented in tables 1 and 2. MPB-caused mortality was observed in the Wyoming plots prior to cutting but no MPB-caused mortality has been observed since cutting. Plots at the Colorado locations have not been exposed to MPB infestations.

Diameter growth was based on trees within the CIP and was calculated for only those trees alive at the time of remeasurement. Diameter growth for each tree was calculated by subtracting its DBH at installation from its DBH at remeasurement. As calculated in this manner

Table 1— Dates for installation, cutting, and remeasurement; number of plots; and age of site index trees for the plots at the five locations.

	Plot name				
Characteristics	**Brush Creek**	**Divide Peak**	**North Savery**	**CO State Forest**	**KOA**
Date installed	August 1985	September 1984	June 1985	August 1984	September 1987
Number of plots	5	4	4	4	4
GSL's of cut plots	40, 60, 80, 120	40, 100, 120	40, 80, 120	40, 80, 120	80, 100, 120
Date cut	July 1987	August 1986	August 1986	July 1985	July 1990
Date remeasured	July 1997	August 1997	August 1997	July 1997	August 1999
Age of site index trees	>90 yrs	>130 yrs	>105 yrs	>90 yrs	>85 yrs

Table 2— Elevation, site index, trees per acre, and percent mortality in the CIP between installation and remeasurement by location and GSL.

			Trees per acre		
Location/GSLs	**Elevation (ft)**	**Site index**	**Before cut**	**After cut**	**CIP mortality**
Brush Creek (WY)					
GSL 40	8480	67	674	78	28%
GSL 60	8460	71	283	77	2%
GSL 80	8460	67	567	150	6%
GSL 120	8480	69	683	268	5%
Control (GSL 234)	8480	67	535		3%
Colorado State Forest (CO)					
GSL 40	8900	58	279	104	0%
GSL 80	8910	62	227	187	1%
GSL 120	8850	71	572	288	4%
Control (GSL 197)	8930	68	526		7%
Divide Peak (WY)					
GSL 40	8340	72	520	73	40%
GSL 100	8320	78	560	184	18%
GSL 120	8320	80	529	206	10%
Control (GSL 197)	8280	78	267		5%
KOA (CO)					
GSL 80	8820	62	452	206	2%
GSL 100	8820	64	364	224	0%
GSL 120	8820	64	364	281	1%
Control (GSL 155)	8820	61	416		2%
North Savery (WY)					
GSL 40	8340	72	371	49	15%
GSL 80	8340	67	984	223	5%
GSL 120	8340	68	917	299	2%
Control (GSL 270)	8340	73	589		11%

for these sets of plots, diameter growth or periodic annual increment for the partially cut stands represents a mixture of annual increments of growth under the uncut and partially cut stand conditions because the trees grew in the uncut situation for one to three growing seasons before the stands were partially cut. The consequences of this situation are discussed later.

Some trees had smaller diameters at the time of remeasurement than they had when the plots were installed. We considered this situation to result from differences in the manner in which the diameters were measured and assigned such trees zero growth. Trees dying between plot installation and plot remeasurement were not included in the calculations of mean diameter growth.

One-way analysis of variance was used to determine if mean diameter growth in the various diameter classes varied significantly among GSLs within each diameter class at each location and among diameter classes within each GSL at each location. If significant variation was found, Tukey's test was used to determine which means were significantly different, $\alpha = 0.05$.

The increase in periodic annual increment (PAI) in BA was calculated in the same manner as for diameter growth. Total BA after marking was subtracted from total BA at remeasurement. The resulting value was divided by the number of years between installation and remeasurement to derive the unadjusted PAI. However, the plots grew in the uncut condition before they were cut (see previous paragraphs on diameter growth) so that the BA after cutting was actually greater than the BA after marking. The time interval between tree selection/marking and tree cutting varied among locations; it was 1 yr for CSF, 2 yr for BCRK, DPEAK, and NSAV, and 3 yr for KOA. Therefore, to derive a more realistic PAI for BA growth, it was assumed that the partially cut plots grew at the same rate as their respective control during the years preceeding their cutting and a percentage of this growth was added to their BA after marking. The amount of the BA growth for the control added to the BA after marking for each of the partially cut plots depended on what percentage of the original BA existed after marking. For example, if the BA after marking was 40 and the BA at plot installation was 200, the BA after marking represented 20% of the original BA (40/200) so 20% of the BA growth for the control was added to the after-marking BA for the partially cut plot. The difference between the adjusted BA and the BA at remeasurement was divided by the number of years between tree cutting and plot remeasurement to derive the adjusted BA PAI.

The susceptibility of each GSL at each location to MPB infestation was determined according to the methods of Amman et al. (1977), Shore and Safranyik (1992), and Anhold et al. (1996).

The current and future susceptibility of each partially cut GSL was also estimated by determining when its BA might reach the BA thresholds of 150 and 120 ft^2/acre (see Obedzinski et al. 1999). In previous work in ponderosa pine, Sartwell and Stevens (1975) believed that BA $\geq$150 ft^2/acre was a critical level for MPB infestation. The BA 150 level was commonly accepted as the critical threshold until Schmid and Mata (1992) suggested the critical threshold might be as low as BA 120 ft^2/acre in ponderosa pine. Although a basal area threshold(s) for lodgepole pine has not been determined, information in McGregor et al. (1987) and Gibson (1989) suggest that 120 ft^2/acre may also be the critical threshold for the MPB in LP. BA 120 is routinely considered the threshold for high hazard LP stands in current evaluations (K.E. Gibson 2002, personal communication). Thus, for comparative purposes, the 150 and 120 ft^2/acre values were used to determine how long it would take the partially cut LP stands to reach these levels. The estimates, based on growth data obtained from each plot, were derived from straight-line projections (SLP) and from a growth and yield model.

For straight-line projections, two BA values were used: the BA after tree marking was completed (i.e., when the plots were installed and leave trees were selected), and the BA at remeasurement. Ordinarily, the BA after marking was plotted for time (year) equal to zero because the non-leave trees were cut soon after selection and marking. However, as indicated in the previous paragraph regarding the determination of BA growth, the trees were not cut within a short time after tree selection and marking so trees in the partially cut stands grew in the uncut condition for 1 to 3 years depending on the location. Therefore, the BAs after marking were adjusted for their growth in the uncut condition as indicated in the previous paragraph regarding the determination of BA growth. The BA at remeasurement was unaffected by the difficulty with the determination of the BA after marking. BA at remeasurement was plotted for when time (year) equalled the number of years between tree cutting and remeasurement. Straight lines were drawn through the two BA values for each GSL and extended until they either intercepted the 120 and 150 BA values or exceeded 100 years.

To determine if our straight-line projections differed substantially from those derived from a growth and yield model, we also estimated the time required to reach the susceptibility thresholds by inputting the stand and growth data for each GSL plot into the growth and yield model GENGYM. GENGYM is a computerized growth and yield model used for projecting future stand conditions in mixed conifer and ponderosa pine stands (Edminster et al. 1991). GENGYM supercedes RMYLD (see Edminster 1978 regarding RMYLD), which was used by Schmid (1987) to estimate the time for ponderosa pine stands to reach susceptibility thresholds.

Some problems inherent in using the straight-line projection and GENGYM methods for estimating future stand conditions are discussed in more detail when the projection estimates are made in the Results and Discussion and Management Implications sections.

Results and Discussion

Diameter Growth

Mean diameter increased in all plots with increases ranging from 0.3 to 3.2 inches (table 3). Increases in mean diameter in the partially cut stands resulted from tree selection criteria and growth. Because smaller diameter trees were generally but not exclusively discriminated against in our design, more smaller trees were generally cut than larger diameter trees. Thus, the initial increase in mean stand diameter immediately after cutting was not a matter of growth, but the removal of a high percentage of the smaller trees. Subsequent to the partial cutting, increases in average diameters resulted from growth. Mean diameter growth in most of the partially cut plots generally exceeded 0.8 inches during the first 10 yr after cutting, while mean diameters in the control plots increased ≤0.6 inches (table 3).

Brush Creek. Among GSLs, mean growth rates within the 7- to 12-inch diameter classes in the partially cut GSLs (GSLs 40, 60, 80, and 120) were significantly greater than the mean growth rates for comparable diameters in the control (table 4). In the 13-inch class, the mean growth rate in the GSL 60 was significantly greater than the rates in the GSL 120 and control. In the 14-inch class, the mean growth rate in the GSL 60 was significantly greater than that of the control. Mean growth rates in the GSL 40 and GSL 60 were significantly greater in the 10- to 11-inch diameter classes than mean growth rates in the GSL 120 (table 4).

Within each partially cut GSL, mean growth rates were not significantly different among diameter classes (table 4). Within the control, mean growth rates were significantly different among diameter classes and increased with increasing diameter class. Mean growth rates in the 8- to 14-inch classes were generally significantly greater than mean growth rates in the 4- to 7-inch classes.

Table 3— Increases in mean diameter in inches by growing stock level (GSL).

Location /GSL	Mean diameter			Increase between:	
	After installation	After marking	At remeasurement	Installation & marking	Marking & remeasurement
	inches				
Brush Creek (WY)					
GSL 40	7.8	9.7	11.0	1.9	1.3
GSL 60	10.5	12.0	13.4	1.5	1.4
GSL 80	8.4	10.0	11.1	1.6	1.1
GSL 120	7.6	8.9	9.7	1.3	0.8
Control	8.8	8.8	9.1	0.0	0.3
Colorado State Forest (CO)					
GSL 40	7.3	8.0	9.7	0.7	1.7
GSL 80	8.5	8.6	10.0	0.1	1.4
GSL 120	7.6	8.5	9.4	0.9	0.9
Control	7.8	7.8	8.3	0.0	0.5
Divide Peak (WY)					
GSL 40	8.9	10.6	11.3	1.7	0.7
GSL 100	8.7	9.9	10.9	1.2	1.0
GSL 120	9.2	10.4	11.3	1.2	0.9
Control	11.6	11.6	12.0	0.0	0.4
KOA (CO)					
GSL 80	7.4	8.3	9.1	0.9	0.8
GSL 100	8.3	8.9	9.7	0.6	0.8
GSL 120	8.2	8.6	9.1	0.4	0.5
Control	7.8	7.8	8.2	0.0	0.4
North Savery (WY)					
GSL 40	10.4	12.4	13.2	2.0	0.8
GSL 80	7.1	8.4	9.5	1.3	1.1
GSL 120	7.4	8.6	9.5	1.2	0.9
Control	9.0	9.0	9.6	0.0	0.6

Table 4—Mean diameter growth ($\bar{X}$±SD) in inches by 1-inch diameter class for different GSLs at Brush Creek (BCRK) based on 12-yr growth data.

Diameter	GSL 40	GSL 60	GSL 80	GSL 120	Control
			inches		
4					0.0±0.06
5					0.0±0.08
6	1.1[a]			0.8±0.27	0.1±0.14
7	1.1±1.04		1.1±0.39	0.8±0.27	0.2±0.16
8	0.9±0.44	2.2[a]	1.1±0.37	0.8±0.29	0.2±0.18
9	1.0±0.54	1.2±0.37	1.1±0.38	0.8±0.31	0.3±0.19
10	1.4±0.60	1.5±0.74	1.0±0.48	0.8±0.25	0.3±0.18
11	1.2±0.50	1.1±0.48	1.1±0.39	0.8±0.32	0.4±0.23
12	1.2±0.70	1.3±0.44	1.0±0.39	0.8±0.22	0.4±0.18
13	1.3[a]	1.2±0.43	0.8±0.29	0.6±0.22	0.4±0.28
14	1.0[a]	1.3±0.40	1.3±0.46	1.1±0.38	0.6±0.13
15		1.2±0.38			0.4±0.07
16		1.1[a]			0.6[a]

[a] One tree sample

No measurable growth or growth insufficient enough to provide a mean value greater than 0.05 was observed in only the 4- and 5-inch diameter classes in the control (table 4). The greatest growth for any tree in the GSL 40, GSL 60, and GSL 80 was ≥2 inches. Only one tree in the control grew 1.4 inches while the rest of the trees in all diameter classes grew less than 1 inch.

Colorado State Forest. Among GSLs, mean growth rates in the 7- to 9-inch diameter class were signicantly greater in the partially cut GSLs (GSL 40, 80, and 120) than mean growth rates in the control (table 5). In the 10- and 11-inch clases, mean growth rates in the GSL 80 were greater than those of the GSL 120 and control. In other diameter classes, data was insufficient to provide satisfactory tests among the 4 plots.

Within each GSL, mean growth rates were not significantly different among diameter classes in the partially cut GSLs but were significantly different in the control (table 5). Except where diameter classes were represented by only one or two trees, mean growth rates in the 9- to 12-inch diameter clases within the control were significantly greater than growth rates for lesser diameter classes but were not significantly different from each other.

Growth rates for individual trees in the GSL 40 and GSL 80 commonly exceeded 2 inches while individual trees in the control rarely exceeded 0.9 inches. While the difference can be attributed to the different stocking levels in the partially cut plots versus the control, the difference is also attributable to previous stand treatments.

Table 5—Mean diameter growth ($\bar{X}$±SD) in inches by 1-inch diameter class for different GSLs at Colorado State Forest (CSF) based on 12-yr growth data.

Diameter	GSL 40	GSL 80	GSL 120	Control
		inches		
3				0.1±0.15
4				0.1±0.10
5		0.7[a]	0.6±0.13	0.2±0.17
6	1.6±0.26	1.2±0.44	0.8±0.40	0.3±0.20
7	1.7±0.29	1.2±0.41	0.9±0.34	0.4±0.24
8	1.7±0.38	1.4±0.38	0.9±0.31	0.5±0.25
9	1.7±0.33	1.5±0.40	0.9±0.28	0.6±0.22
10	1.7±0.21	1.5±0.47	0.9±0.35	0.6±0.23
11	1.4[a]	1.4±0.47	0.9±0.40	0.7±0.30
12		1.7[a]	1.0±0.25	0.7±0.23
13			1.4±0.64	0.8[a]
14				0.3±0.35
15				0.5[a]

[a] One tree sample

The CSF GSL 40 and GSL 80 plots were superimposed on an area that had previously been partially cut to about GSL 80 years prior to plot installation. Thus, trees in these 2 plots had adjusted to the reduced competition and were already growing at an increased rate before we installed our plots. Our additional partial cutting probably further enhanced the growth rates. The combined influence of the 2 partial cuts explains why trees in these plots generally exhibited growth rates superior to the growth rates of trees in comparable GSLs from the other locations.

Divide Peak. Mean growth rates for 9- to 13-inch diameter classes in the partially cut plots (GSL 40, 100, and 120) were significantly greater than those of the control; growth rates in the partially cut plots were generally double those in comparable diameter classes in the control (table 6). Mean growth rates in the 7-inch class were not significantly different among GSLs. In the 8-inch diameter class, the mean growth rate in the GSL 120 was greater than that of the control but rates for the GSL 40 and 100 were not significantly different (table 6).

Within GSLs, mean growth rates were significantly different among diameter classes in all GSLs (table 6). In the GSL 40, mean growth rates in the 6- and 7-inch diameter classes were significantly less than the rate in the 15-inch class; all other diameter classes were not significantly different from each other. In the GSL 100, the rate for the 8-inch class was significantly less than the rate for the 13-inch class; rates for all other diameter classes were not significantly different from each other. In the GSL 120, the mean growth rate for the 7-inch diameter class was significantly less than the rates for the 9- to 13-inch diameter classes; other diameter classes were not significantly different from each other. Mean growth rates for the 4- to 8-inch and 10-to 15-inch diameter classes in the control were significantly less than the growth rate for the 19-inch class.

KOA. Among GSLs, mean diameter growth rates were significantly variable within the 7- to 10-inch diameter classes but not significantly different in the 11- to 13-inch classes (table 7). Mean growth rates in the GSL 80 were significantly greater than the rates for the other GSLs in the 7- to 10-inch classes while mean growth rates among the other GSLs were not significantly different in the same classes.

Mean diameter growth rates within GSLs were highly variable. Although significant differences were present in each GSL, significant differences usually existed between only 2 diameter classes in each GSL while the other diameter classes were not signicantly different. Only the control exhibited a trend in mean growth rates; growth rates increased with increasing diameter (table 7).

North Savery. Among GSLs, mean diameter growth varied significantly. Generally, mean diameter growth in the 7- to 12-inch diameter classes in the partially cut plots was significantly greater than those in the same diameter classes in the control; only in the 13-inch class were differences nonsignificant (table 8). In most cases, growth rates in the partially cut plots were more than double those in comparable diameter classes in the control (table 8). Average diameter growth rates exceeded 1 inch in some diameter classes in each of the partially cut

Table 6—Mean diameter growth ($\bar{X}$±SD) in inches by 1-inch diameter class for different GSLs at Divide Peak (DPEAK) based on 13-yr growth data.

Diameter	GSL 40	GSL 100	GSL 120	Control
		inches		
4				0.2±0.21
5	1.2±0.78		0.8[a]	0.3±0.17
6	0.8±0.32		0.7±0.42	0.2±0.25
7	0.3±0.16	0.6±0.33	0.4±0.26	0.4±0.32
8	0.8±0.31	0.7±0.29	0.8±0.39	0.4±0.29
9	1.3±0.71	0.8±0.38	0.9±0.39	0.4±0.35
10	1.0±0.29	0.9±0.38	0.8±0.34	0.4±0.29
11	1.0±0.41	0.9±0.47	0.8±0.33	0.4±0.30
12	1.5±0.31	0.8±0.21	0.9±0.38	0.4±0.24
13	1.9±0.14	1.3±0.18	0.9±0.40	0.4±0.25
14	1.8[a]	1.2[a]	0.8±0.39	0.4±0.26
15	1.8±0.90		1.0±0.23	0.3±0.26
16	1.0[a]			0.5±0.27
17	0.5[a]			0.5±0.23
18				0.4±0.21
19				1.0±0.60

[a] One tree sample

Table 7—Mean diameter growth ($\bar{X}$±SD) in inches by 1-inch diameter class for different GSLs at KOA (KOA) based on 12-yr growth data.

Diameter	GSL 80	GSL 100	GSL 120	Control
		inches		
4				0.0±0.09
5	0.6±0.21	0.1a	0.3±0.22	0.1±0.11
6	0.7±0.20	0.5±0.21	0.4±0.22	0.3±0.17
7	0.9±0.31	0.4±0.20	0.4±0.25	0.3±0.17
8	0.9±0.28	0.5±0.23	0.5±0.23	0.5±0.18
9	0.9±0.35	0.5±0.22	0.5±0.20	0.5±0.19
10	1.0±0.36	0.5±0.36	0.5±0.24	0.6±0.15
11	0.7±0.33	0.6±0.25	0.6±0.24	0.6±0.19
12	0.5±0.21	0.9±0.28	0.4±0.28	0.8±0.17
13		0.7a	0.6a	
14			1.1a	0.4a
15				
16	0.7a			

[a] One tree sample

Table 8—Mean diameter growth ($\bar{X}$±SD) in inches by 1-inch diameter class for different GSLs at North Savery (NSAV) based on 13-yr growth data.

Diameter	GSL 40	GSL 80	GSL 120	Control
		inches		
4		0.4[a]		0.2±0.15
5		0.5±0.24	0.5±0.20	0.1±0.13
6		0.6±0.41	0.6±0.31	0.1±0.16
7		1.0±0.39	0.8±0.32	0.2±0.17
8		1.1±0.38	0.8±0.27	0.3±0.21
9		1.3±0.37	0.8±0.36	0.4±0.22
10	0.9±0.28	1.3±0.49	1.0±0.31	0.4±0.23
11	0.8±0.31	1.3±0.34	1.1±0.47	0.4±0.26
12	0.8±0.19	1.3±0.53	1.1±0.39	0.5±0.23
13	0.7±0.49		0.9±0.31	0.4±0.27
14	1.0±0.30			0.4±0.25
15	1.2±0.49			0.5±0.23
16	1.0[a]			0.6±0.17
17				0.6[a]
18				0.7[a]

[a] One tree sample

GSLs while 0.6 inch was the highest average growth rate in the control (table 8).

Mean diameter growth varied significantly among diameter classes within the GSL 80, 120, and control but nonsignificantly in the GSL 40. In the GSL 40, mean growth ranged from 0.7 to 1.2 inches in the various diameter classes with no distinctive trend (table 8). In the GSL 80, GSL 120, and control, mean diameter growth increased from the lowest diameter classes to the highest diameter classes (table 8). Mean growth rates in the 5- and 6-inch classes in the GSL 80, GSL 120, and control were significantly less than rates in larger diameter classes in their respective GSLs (table 8).

What do these growth rates mean in regard to individual tree and stand susceptibility to MPB infestation in unmanaged and managed stands? Because a specific growth rate threshold that separates susceptible LP trees from nonsusceptible LP trees has not been determined in terms of a fraction of an inch per year, or inches per 10-year period, it is difficult to say which growth rates are characteristic of susceptible trees and which are characteristic of nonsusceptible trees. That is, are trees growing at the rate of ≤0.5 inches per 10 years, more susceptible than trees growing at 0.6 or 0.7 inches per 10 years, or some larger rate? Although the literature does not directly address susceptible vs. nonsuceptible growth rates, some indirect evidence is pertinent.

Mahoney's periodic growth ratio (PGR) is the ratio of the current 5-year radial increment divided by the previous 5-year radial increment of dominant and

co-dominant LP trees, i.e., growth for years 1-5 divided by growth for years 6-10. If the average PGR for the stand is <0.9, the stand is considered susceptible (Mahoney 1978). While we did not calculate PGRs for the various plots, the growth rates in the partially cut plots were generally greater than those of the respective controls. PGRs for these plots would probably be >1.0 and would thus indicate nonsusceptible status. The growth rates for the controls probably didn't change over the measurement period. Their PGRs are probably ≤1.0 so the controls would be considered susceptible.

On first thought, the reader might conclude that future PGRs for partially cut stands would be continually >1.0 because the trees in those stands would exhibit increasing growth rates as they take advantage of the reduced competition. However, the trees will eventually reach a point where their annual radial increment is no longer increasing and may even decrease in relation to previous annual increments. If growth rates for 5 years are equal or less than those of the previous years, the PGRs for the partially cut plots probably become 1.0 or <1.0 so the stands would be considered susceptible. Thus, if MPB infestations do not develop in partially cut stands despite ≤1.0 PGRs, Mahoney's system wouldn't appear applicable to managed stands.

While a specific growth rate threshold is not available, Amman (1989) suggests that radial growth rates of 0.02 to 0.04 inches/yr (0.20 to 0.40 inches/10 yr) are too small to reduce MPB-caused tree mortality in partially cut LP stands. If such rates are characteristic of susceptible stands, then the control stands in our five locations would be susceptible (tables 4-8) and most of the partially cut stands except the the KOA GSLs and some GSL 120s would be nonsusceptible. However, within all the partially cut stands except the CSF GSL 40 and GSL 80, diameter growth rates <0.50 inches per 12 to 13 years (radial growth = 0.25 inches) were evident in some susceptible-size trees. While most of the trees are exhibiting nonsusceptible growth rates, some trees, especially those in low diameter classes, are exhibiting susceptible growth rates and, therefore, may function as primary focus trees. Future inventories of these plots will determine if trees with low growth rates become the primary focus trees for the MPB.

Large diameter trees are usually the first trees in a stand to be attacked by the MPB (Cole and Amman 1969, Mitchell & Preisler 1991). Whether such trees are attacked because (1) they represent a visual size attractive to the MPB (Shepherd 1966), or (2) they have low growth rates and therefore issue some physiologically susceptible signal, or (3) size, growth rate, and physiological condition act in unison, remains to be determined. Future inventories of these plots could also determine whether diameter, growth rate, or a combination of diameter, growth rate, and physiological condition plays the most important role in creating the primary focus tree. If diameter growth is more important than tree diameter for attracting attacking MPBs, then trees of all diameters should be attacked because highly susceptible trees are found in a wide range of diameter classes.

Basal Area Growth

Basal area increased in all plots in the five locations except in the BCRK, DPEAK, and NSAV GSL 40s, and the DPEAK GSL 100 (table 9). BA growth generally appeared greater in the partially cut plots than in their respective controls (table 9). Apparent increases in BA were greatest in either the GSL 80 or GSL 120 plots. The largest numerical increase in basal area was in the CSF GSL 80, probably because this plot was superimposed on a stand that had been previously cut (table 9).

Total BA decreased in the BCRK, DPEAK, and NSAV GSL 40s where 80% or more of the original BA was removed because a substantial number of the residual trees were windthrown. Removal of more than 30% of the original BA can cause significant loss in the residual stand because the residual trees lack windfirmness and are easily toppled (Alexander 1972). The CSF GSL 40 did not suffer substantial windthrow because this stand had been cut to about BA 80 before we superimposed a GSL 40 on it. Apparently, a GSL 40 can be developed if an uncut stand is initially cut to a BA ≥80, allowed to grow at that level for 10 to 20 years, and then cut to a GSL 40.

The DPEAK GSL 100 was the only partially cut plot of higher stocking that did not exhibit an increase in BA. This plot has an *Armillaria* pocket in the CIP and had lost 12 trees to *Armillaria* by July 1997. Trees were also lost to windthrow and scolytids which may have been directly related to the *Armillaria* presence. The loss in BA from these causes was sufficient enough to negate increases in BA in the healthy trees.

MPB Susceptibility Estimates

Amman et al. (1977) method. Based on the Amman et al. (1977) stand susceptibility system, all of the plots at the Wyoming locations rated moderate in susceptibility when the plots were installed, after cutting, and at remeasurement (table 10). Some DPEAK and NSAV plots might have been ranked high rather than moderate because the values for the latitude-elevation factor for

Table 9— Unadjusted and adjusted periodic annual increment (PAI) in basal area by growing stock level (GSL). Unadjusted values represent the average increment per year between the BA after marking and the BA at remeasurement and assumes the plots were cut immediately after installation. Adjusted values represent the average increment per year between the BA after marking and BA at remeasurement with the BA after marking adjusted for growth in the uncut condition (see Methods section for how the adjustments were made).

Location /GSL	Basal area			PAI	
	Installation	After marking	At remeasurement	Unadjusted	Adjusted
	ft² per acre				
Brush Creek (WY)					
GSL 40	223.6	40.3	37.1	-0.27	-0.35
GSL 60	170.2	60.7	73.8	1.09	1.26
GSL 80	216.0	81.2	94.4	1.10	1.27
GSL 120	214.3	116.1	131.9	1.32	1.50
Control	224.1	224.1	232.9	0.73	NA[a]
Colorado State Forest (CO)					
GSL 40	81.8	36.6	53.2	1.28	1.35
GSL 80	88.6	75.2	100.3	1.93	2.03
GSL 120	181.6	113.7	133.7	1.54	1.62
Control	175.9	175.9	186.4	0.81	NA
Divide Peak (WY)					
GSL 40	222.6	44.9	30.4	-1.12	-1.33
GSL 100	229.7	98.9	99.0	0.01	-0.01
GSL 120	245.0	122.9	128.9	0.46	0.52
Control	197.4	197.4	200.4	0.23	NA
KOA (CO)					
GSL 80	135.9	76.4	91.4	1.25	1.47
GSL 100	136.9	97.9	114.2	1.36	1.55
GSL 120	132.9	113.8	125.6	0.98	1.00
Control	138.4	138.4	151.3	1.08	NA
North Savery (WY)					
GSL 40	218.1	40.6	39.0	-0.12	-0.17
GSL 80	273.1	86.8	105.3	1.42	1.83
GSL 120	267.3	121.6	142.9	1.64	2.11
Control	262.6	262.6	266.0	0.28	NA

[a] NA equals not applicable.

these plots intersected near the line separating the moderate risk from the high risk but we conservatively chose this risk factor as moderate.

Similarly, about one-half of the Colorado plots rated moderate while the other half rated high at the time of plot installation (table 10). Most of the Colorado plots rated high after cutting and at remeasurement (table 10). The rating changed for the partially cut plots because average diameter became >8 inches after cutting (table 3) as the result of our discrimination against smaller diameter trees. The Colorado plots rated higher than the Wyoming plots because the elevation-latitude factor rated high rather than moderate.

If the susceptibility ratings under the Amman et al. (1977) system accurately portray the susceptibility of the various GSLs, then partial cutting does not modify stand susceptibility in LP stands where the average age >80 years, the average DBH >8 inches, and larger diameter trees are selected as leave trees. This conclusion differs with results from partial cutting in ponderosa pine stands where partial cutting appears to lower susceptibility even though larger diameter trees are retained (see Schmid and Mata 1992).

Shore & Safranyik (1992) method. Based on the Shore and Safranyik (1992) susceptibility rating system, the stand ratings ranged from 14 to 70 at installation (table 11). None of the GSLs rated >70 because they either had <100% of the stand in trees >6 inches, the density was below 751 stems per ha, the location factor was not optimal, or a combination of less than optimal ratings for all three of these factors.

After marking and at remeasurement, the ratings for the partially cut GSLs ranged from 7 to 35 while the controls remained essentially the same (table 11). Even though the percentage of susceptible LP increased in most of the partially cut GSLs, the decrease in the

Table 10—Susceptibility ratings for each GSL plot based on the rating method of Amman et al. (1977).

Location/GSL	At installation	After marking	After remeasurement
Brush Creek (WY)			
GSL 40	Moderate	Moderate	Moderate
GSL 60	Moderate	Moderate	Moderate
GSL 80	Moderate	Moderate	Moderate
GSL 120	Moderate	Moderate	Moderate
Control	Moderate	Moderate	Moderate
Colorado State Forest (CO)			
GSL 40	Moderate	High	High
GSL 80	High	High	High
GSL 120	Moderate	High	High
Control	Moderate	Moderate	High
Divide Peak (WY)			
GSL 40	Moderate	Moderate	Moderate
GSL 100	Moderate	Moderate	Moderate
GSL 120	Moderate	Moderate	Moderate
Control	Moderate	Moderate	Moderate
KOA (CO)			
GSL 80	Moderate	High	High
GSL 100	High	High	High
GSL 120	High	High	High
Control	Moderate	Moderate	High
North Savery (WY)			
GSL 40	Moderate	Moderate	Moderate
GSL 80	Moderate	Moderate	Moderate
GSL 120	Moderate	Moderate	Moderate
Control	Moderate	Moderate	Moderate

number of stems lowered the ratings for most of the partially cut GSLs.

In contrast to the Amman et al.(1977) rating system, the Shore and Safranyik (1992) rating system indicates that stand susceptibility is substantially lowered by partial cutting. If their range for stand susceptibility (0 to 100) is arbitrarily subdivided into low (0 to 35), moderate (36 to 70), and high (71 to 100) classes, the partially cut GSLs fall in the low susceptibility class. This occurs because the tree density and location factors are less than optimal for MPB infestation.

Susceptibility ratings for the partially cut GSLs are not likely to change significantly in next 20 years, and perhaps longer, under the Shore and Safranyik (1992) system. After partial cutting, the percentage of susceptible pine is near or at 100% because our design discriminated against the smaller diameter lodgepole and other species; therefore, the rating for this factor will not change. Unless the density factor is at or near threholds where it changes (primarily, 250 or 750 stems per ha), the rating for this factor will also not change in the 20 to 40 years. If anything, the density factor will fall into a lower susceptibility class as individual trees die and tree density decreases. In 40 or more years, the density factor could increase if ingrowth occurs. However, GENGYM estimates that GSL 80 stands will not have ingrowth for more than 40 years and stands with greater GSLs may not have ingrowth, so the density factor will not increase significantly. Because the various susceptibility factors in the Shore and Safranyik method will not significantly change with future growth of the existing trees in the GSLs, the future susceptibility of the partially cut GSLs appears to remain essentially constant until substantial ingrowth occurs or the larger diameter trees die. This differs sharply with the situation in ponderosa pine wherein the susceptibility of partially cut stands with BAs $\geq$80 are thought to increase with BA growth on the residual stand (see Obedzinski et al. 1999). However, because BA growth on residual trees is not part of the Shore and Safranyik system for LP, such growth does not influence future susceptibility. It remains to be seen if partially cut LP stands become more susceptible in the future as a result of growth on existing trees or the susceptibility remains unchanged as the Shore and Safranyik system predicts.

Table 11—Susceptibility ratings for each GSL plot based on the rating method of Shore and Safranyik (1992).

Location/GSL	At installation	After marking	After remeasurement
Brush Creek (WY)			
GSL 40	51	7	7
GSL 60	35	7	7
GSL 80	65	35	35
GSL 120	49	35	35
Control	67	67	68
Colorado State Forest (CO)			
GSL 40	14	15	15
GSL 80	15	15	15
GSL 120	27	15	15
Control	27	27	28
Divide Pk (WY)			
GSL 40	67	7	7
GSL 100	70	35	35
GSL 120	68	35	35
Control	35	35	35
KOA (CO)			
GSL 80	63	32	32
GSL 100	68	35	35
GSL 120	66	35	35
Control	65	65	67
North Savery (WY)			
GSL 40	69	7	7
GSL 80	34	34	34
GSL 120	34	34	35
Control	67	67	69

Anhold et al. (1996) method. Based on the Anhold et al. (1996) method, all stands except the CSF GSL 80 rated low in susceptibility at installation because either the number of trees per acre was greater than the upper limit of the "zone" of high susceptibility or the quadratic mean diameter was <8 inches (table 12). The CSF GSL 80 rated high susceptibility because the number of trees per acre fell within the "zone" of high susceptibility as a result of the plot being superimposed on a stand that had been partial cut prior to our establishment of the plot.

After cutting and at remeasurement, all GSL 40, GSL 60, and control stands rated low in susceptibility. The partially cut GSL 40 and 60 stands rated low because the number of trees per acre fell below the lower limit of the "zone" of high susceptibility. Control stands rated low because the number of trees per acre remained greater than the upper limit of the "zone" of high susceptibility.

After cutting and at remeasurement, all GSL 80, GSL 100, and GSL 120 stands rated high because the number of trees per acre fell within the "zone" of high susceptibility (table 12). The high susceptibility ratings for the GSL 80 to GSL 120 stands is contrary to the results of partial cutting in LP wherein tree mortality (and presumably susceptibility) was reduced for stands with BA <120 (see McGregor et al. 1987) and in ponderosa pine wherein stands with GSL <120 were considered less susceptibile (see Schmid and Mata 1992). If the Anhold et al. method accurately estimates susceptibility in LP stands, then partial cutting to GSLs of 80 to 120 would be unwise.

Straight-line & GENGYM projections. Straight-line projections (SLP) indicate that GSL 40 stands will take from 85 to more than 100 years to reach the BA threshold of 150 ft^2 per acre while GENGYM projections indicate the same GSL 40 stands will take from 68 to more than 100 years (table 13). Similar time periods are estimated for most of the GSL 40 stands with respect to the BA threshold of 120 ft^2 per acre (table 13). However, the timeframes of >100 years for the BCRK, DPEAK, and NSAV GSL 40s (figures 1, 3, and 5 and table 13) are misleading. Because these GSLs lost trees to windthrow between when they were cut and when they were remeasured, the stocking levels decreased below the design levels. Therefore, both BA growth and total BA was much less than what might be expected if no windthrow had occurred. This causes the SLP method to predict the eventual demise of these stands (see figures 1, 3, and 5) and the GENGYM method to predict shorter time

Table 12—Susceptibility ratings for each GSL plot based on the rating method of Anhold et al. (1996).

Location/GSL	At installation	After marking	After remeasurement
Brush Creek (WY)			
GSL 40	Low	Low	Low
GSL 60	Low	Low	Low
GSL 80	Low	High	High
GSL 120	Low	High	High
Control	Low	Low	Low
Colorado State Forest (CO)			
GSL 40	Low	Low	Low
GSL 80	High	High	High
GSL 120	Low	High	High
Control	Low	Low	Low
Divide Peak (WY)			
GSL 40	Low	Low	Low
GSL 100	Low	High	High
GSL 120	Low	High	High
Control	Low	Low	Low
KOA (CO)			
GSL 80	Low	High	High
GSL 100	Low	High	High
GSL 120	Low	High	High
Control	Low	Low	Low
North Savery (WY)			
GSL 40	Low	Low	Low
GSL 80	Low	High	High
GSL 120	Low	High	High
Control	Low	Low	Low

periods to reach the BA 150 level than will actually occur. When the BA growth and total BA are adjusted for this mortality (figures 1, 3, and 5, and table 13), the estimates are more realistic although they still project these GSL 40s to take >100 years to reach the two thresholds.

In contrast to the BCRK, DPEAK, and NSAV GSL 40s, the CSF GSL 40 (figure 2) is estimated to reach the BA 150 threshold in 68 to 85 years and the 120 threshold in 49 to 62 years (figure 2 and table 13). Although these estimates represent more realistic estimates for the times required by a GSL 40 to reach the BA thresholds of 150 and 120 ft^2 per acre, they are also somewhat misleading. Because the CSF GSL 40 was superimposed on a previously thinned area, the growth rate may be greater than what would be expected after an initial partial cut in an unmanaged stand with BA ≥200 ft^2/acre. Despite this, the timeframe for the CSF GSL 40 is probably more typical for a windfirm stand than the time frames for the windthrown GSL 40s.

The time intervals for the GSL 80 plots to reach the BA 150 threshold ranged from 30 to 56 years (table 13) with time estimates differing substantially between estimation methods for the BCRK and CSF GSL 80s. The longest time interval (55-56 years) occurred in the BCRK and KOA GSL 80s.

The difference between the SLP and GENGYM estimates for the BCRK GSL 80 is most likely caused by the tree mortality. Because this GSL 80 had 6% tree mortality, the SLP estimate deflected the projection to a longer time period and overestimated the time (56 years) to reach BA 150. Under the same conditions, GENGYM did not take into account tree mortality and applied the growth data to the stand as if no trees had died. This caused the GENGYM estimate to understate the time required to reach BA 150.

The difference between the two estimates for the CSF GSL 80 probably results from the compound effect of growth rate and the incorporation of that growth rate into the GENGYM model. While the CSF GSL 80 had 1% mortality, the amount of mortality was probably an insignificant contributor to the difference in the two estimates. More importantly, the GSL 80 was superimposed on a stand that had been partially cut years before the plot was installed. The growth rates for the individual trees were greater than what might be expected from an uncut stand. When these growth rates are incorporated into the GENGYM model on a 10-year basis, the increase in BA is greater than for the SLP method. Thus, the GENGYM estimate is considerably less than the SLP estimate.

Table 13— Approximate number of years for various GSLs to reach the susceptibility thresholds of basal areas of 120 and 150 as derived from straight-line and GENGYM projections.

GSL 120 threshold

	GSL 40		GSL 60		GSL 80		GSL 100		GSL 120		Control	
	Line proj.	GENGYM	Line proj.	GENGYM	Line proj.	GENGYM	Line proj.	GENGYM	Line proj.	GENGYM	Line proj.	GENGYM
Brush Creek (WY)	>100 (>100)[a]	>100 (>79)[a]	49	42	32	22			2	3	0	0
Colorado State Forest (CO)	62	49			22	19			4	3	0	0
Divide Peak (WY)	>100 (>100)	>100 (>73)					24 (>100)	26 (12)	0	0	0	0
KOA (CO)					32	33	13	21	4	6	0	0
North Savery (WY)	>100 (>100)	>100 (>100)			18	18 (19)			0	0	0	0

GSL 150 threshold

	GSL 40		GSL 60		GSL 80		GSL 100		GSL 120		Control	
	Line proj.	GENGYM	Line proj.	GENGYM	Line proj.	GENGYM	Line proj.	GENGYM	Line proj.	GENGYM	Line proj.	GENGYM
Brush Creek (WY)	>100 (>100)	>100 (>100)	74	64	56	38			23	17	0	0
Colorado State Forest (CO)	85	68			38	30			22	15	0	0
Divide Peak (WY)	>100 (>100)	>100 (>100)					41 (>100)	43 (28)	50	22 (15)	0	0
KOA (CO)					55	54	34	46	33	29	11	11
North Savery (WY)	>100 (>100)	>100 (>100)			35	30 (33)			14	15 (14)	0	0

[a] For some GSLs, two time estimates are given because straight-line projections and GENGYM do not adjust for significant tree mortality evident in these GSLs subsequent to cutting, i.e., between cutting and remeasurement. The first time estimate represents the number of years wherein the estimate was adjusted for the mortality. The numbers in parentheses represent an estimate based on the unadjusted tree numbers. See figures 1-5.

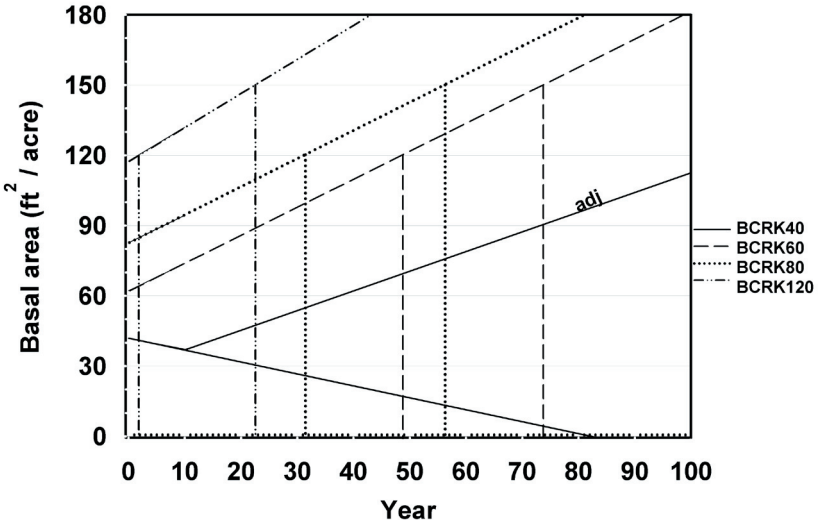

Figure 1— Years required for the partially cut stands at the Brush Creek location to reach basal area (BA) susceptibility thresholds of 150 and 120 ft^2/acre based on straight-line projections. Because mortality caused the BA at remeasurement to be less than the BA after marking for the GSL 40, the initial straight-line projection indicates the demise of the stand. However, unless further mortality occurs, the trees existing at remeasurement will grow and BA will increase, the line below the "adj" represents the adjusted projection for the GSL when a BA growth rate is applied to the BA at remeasurement.

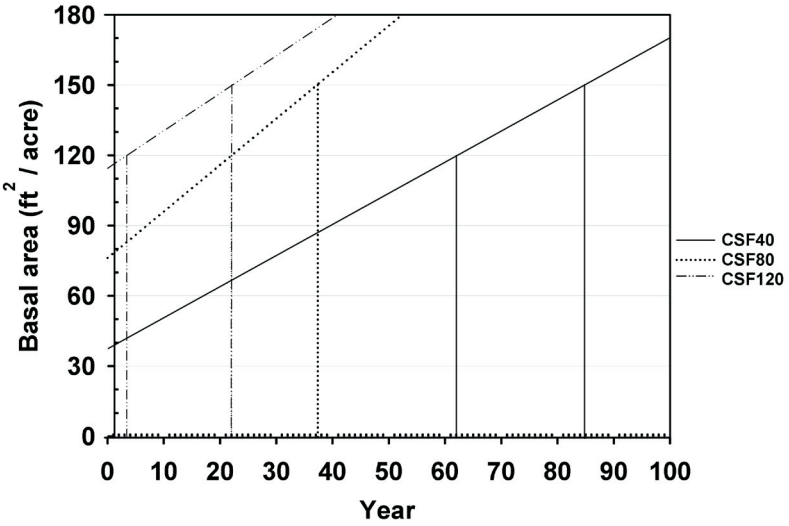

Figure 2—Years required for the partially cut stands at the Colorado State Forest location to reach basal area (BA) susceptibility thresholds of 150 and 120 ft²/acre based on straight-line projections.

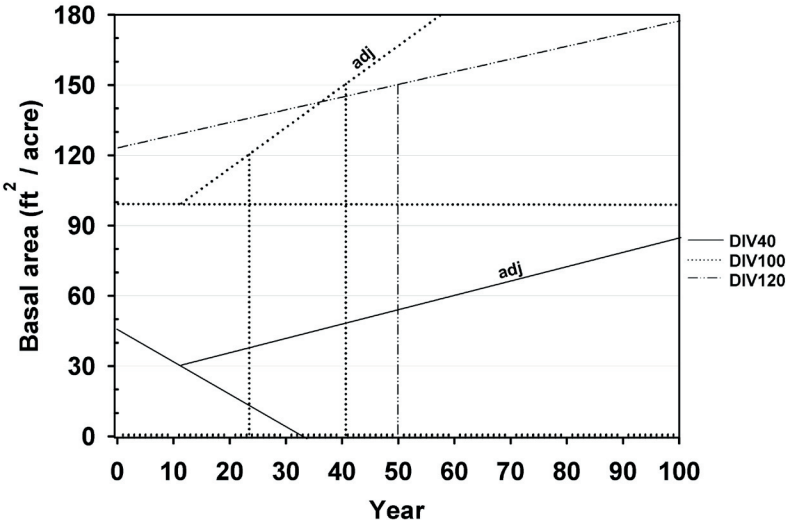

Figure 3—Years required for the partially cut stands at the Divide Peak location to reach basal area (BA) susceptibility thresholds of 150 and 120 ft²/acre based on straight-line projections. Because mortality caused the BA at remeasurement to be less than or equal to the BA after marking for the GSL 40 & GSL 100, the initial straight-line projections indicate the stands will not increase in BA. However, unless further mortality occurs, the trees existing at remeasurement will grow and BA will increase, the line below the "adj" represents the adjusted projection for the GSL when a BA growth rate is applied to the BA at remeasurement.

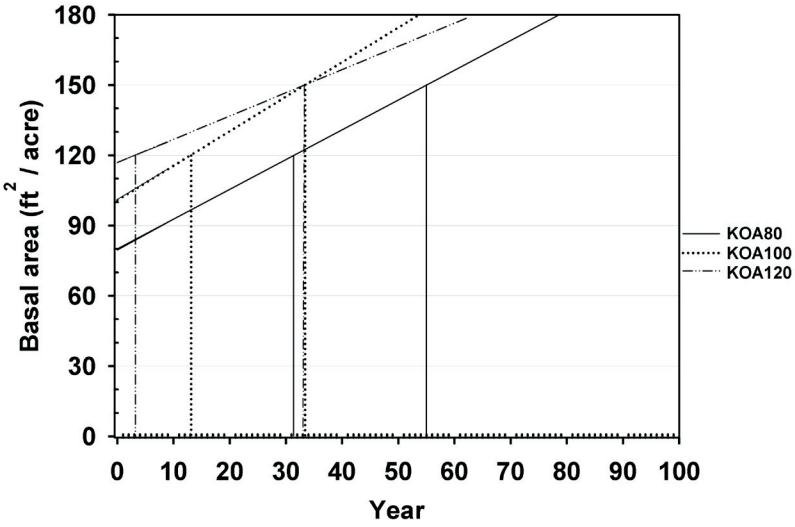

Figure 4—Years required for the partially cut stands at the KOA location to reach basal area (BA) susceptibility thresholds of 150 and 120 ft²/acre based on straight-line projections.

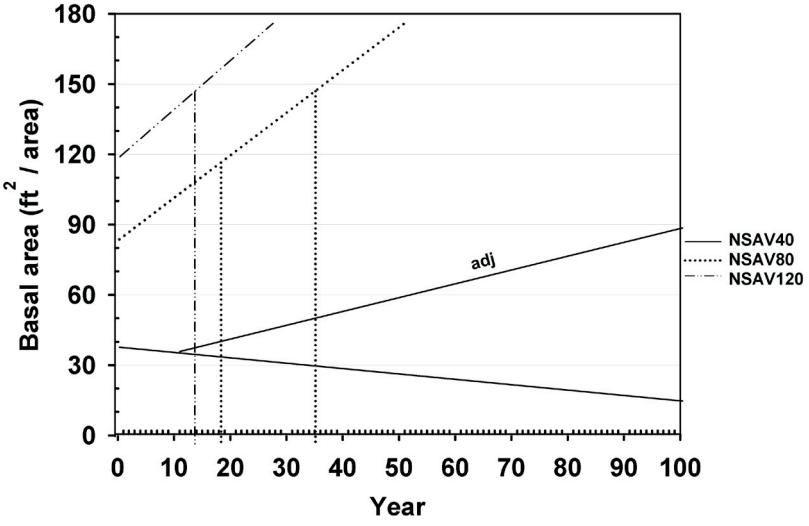

Figure 5—Years required for the partially cut stands at the North Savery location to reach basal area (BA) susceptibility thresholds of 150 and 120 ft²/acre based on straight-line projections. Because mortality caused the BA at remeasurement to be less than the BA after marking for the GSL 40, the initial straight-line projection indicates the demise of the stand. However, unless further mortality occurs, the trees existing at remeasurement will grow and BA will increase, the line below the "adj" represents the adjusted projection for the GSL when a BA growth rate is applied to the BA at remeasurement.

The NSAV GSL 80 attained BA 150 in 33 to 35 years (table 13) with the unadjusted SLP and GENGYM estimates almost identical. However, when the GENGYM estimate was corrected for the 5% tree mortality, its estimate is several years less than the SLP estimate (table 13).

If the basal area threshold is lowered to 120 ft², then the time interval for the different GSL 80s to reach that level ranges from 18 to 33 years depending on the method of estimation. Again, the BCRK and KOA GSL 80s took the longest (32 years), while the other GSL 80s will take about 18 to 22 years depending on the method of estimation. The problems inherent in the estimates for the BCRK and KOA GSL 80s when the BA equaled 150 are also present in the time estimates when the BA threhold equaled 120.

Comparing time intervals for LP GSL 80s with those for ponderosa pine GSL 80s (see Obedzinski et al. 1999), the LP GSL 80s will reach the basal area threshold of 150 ft² before the ponderosa pine GSL 80s do. Similarly, the LP GSL 80s will reach the threshold of 120 ft² about the same time or sooner than ponderosa pine GSL 80s. This relationship probably results from higher site indicies for most of the LP GSLs than for the ponderosa pine GSLs, and a greater number of trees per acre on the LP sites than on the ponderosa pine plots. Thus, even though average DBHs on the LP sites are less than on the ponderosa pine sites, the greater site productivity coupled with the greater number of trees equates to a more rapid increase in BA on the LP sites.

The time intervals for the GSL 120s to reach the BA threshold of 150 ft² ranged from 14 to 50 years (table 13) although the majority of the GSL 120s took <25 years. The DPEAK SLP estimate of 50 years resulted from the 10% tree mortality which created a longer estimate when incorporated into the SLP. The KOA GSL 120 is estimated to take 29 to 33 years to achieve the 150 threshold (figure 4, table 13) probably because the average DBH was 8.5 and the basal area PAI was <1.

In comparison to the lone PP GSL 120 (see Obedzinski et al 1999), most of the LP GSL 120s achieved the 150 threshold before the ponderosa pine GSL 120. As with the GSL 80s, the lesser time intervals for the LP GSL 120s are probably attributable to greater site productivity and the greater number of trees per acre even though the trees are generally smaller than those on the comparable ponderosa pine site.

Management Implications

Although the partial cutting of unmanaged LP stands to a GSL 40 (or perhaps between GSL 40 and GSL 60) with one cutting may be desirable from a MPB management perspective, the option is undesirable because of windthrow risk. As Alexander (1972, 1974) suggests, the initial cutting in single-storied old-growth stands in low windfall risk situations could remove up to 30% of the BA in overstory trees. While stands in this study may not be considered old-growth, where more than 80% of the original BA was cut in the GSL 40 plots and Alexander's recommendation was exceeded by about 50%, three of the four GSL 40s lost trees to windthrow and their stocking levels decreased below the designated level. Thus, creating a windfirm GSL 40 via a single partial cut in an unmanaged stand with BA ≥200 seems unlikely because >75% of the original BA is removed. However, if a GSL 40, or any GSL ≤60, is deemed desirable from a MPB management perspective and time is not a limiting factor, a windfirm GSL 40 might be achieved with

two partial cuts in a manner similar to the cuttings in the CSF GSL 40. In that GSL 40, the unmanaged stand was initially cut to about GSL 80. After windfirmness developed, the stand was further cut to the GSL 40 and windthrow has not been evident since the second cutting. While the CSF GSL 40 may be an exceptional case, the silvicultural prescriptions creating it offer a possible means of achieving a windfirm GSL 40.

In the reports of Amman (1989) and Gibson (1989), partial cutting reduced the susceptibility of LP stands to MPB infestations. How long the partially cut stands remain relatively nonsusceptible depends on the threshold for MPB infestation and the residual stocking level of the stand. If a BA 120 threshold for MPB infestation is valid for LP as it appears to be for the MPB in ponderosa pine (see Gibson's 2002 personal communication, Schmid and Mata 1992, Schmid et al. 1994), then partial cutting an unmanaged stand to a GSL 120 will reduce stand density and improve tree growth but will still leave it in a susceptible condition. If the threshold for infestation is considered to be BA 150 and reentry into partially cut stands occurs about every 25 years, then most GSL 120 stands may reach that level in <25 years (table 13), well before the scheduled reentry.

Stands cut to GSLs ≤100 should be less susceptible than GSL 120 stands but may enter the susceptible category rather quickly. Stands of GSL 80 may reach the BA 120 level in <25 years (table 13), well before scheduled reentry unless tree mortality exceeds 5%. If the threshold for infestation is considered to be BA 150 and reentry occurs every 25 years, then most GSL 80 stands will probably take more than 30 years to reach this threshold or well after reentry. Thus, forest managers should be aware of the relationships between threshold levels for epidemic MPB populations, stand growth, and reentry intervals for partially cut stands.

The relationships between MPB infestation thresholds, stand densities, and reentry schedules does not mean that specific stands must be automatically reentered just because stand BAs have exceeded the BA 120 threshold. While it is good management practice to do so, stands exceeding the threshold need not be reentered on the specific reentry date as long as managers increase their vigilance for MPB activity in such stands and are able to readily adjust their silvicultural activities if MPB infestations appear. Past epidemics indicate, however, that stands allowed to exceed the susceptibility threshold become the ignition points for subsequent MPB epidemics. Ignoring susceptible stands or leaving them until well beyond the normal reentry date invites a MPB epidemic.

Both the SLP and the GENGYM methods will give erroneous estimates of future stand conditions if the stands are subject to substantial mortality during the first 10 years after cutting. The SLP method will exaggerate the time required to reach specific BA levels, or in some GSLs, indicate a stand heading toward nonexistence. How much the time estimate will deviate from the actual trend of stand conditions is influenced by the percent of tree mortality, the GSL, and the number of trees per acre in that GSL. In GSL 40s, mortality sufficient to lower the 10-year BA to less than the original BA will cause the SLP method to predict the eventual demise of the stand as evidenced in the BCRK, DPEAK and NSAV GSL 40s (figures 1, 3, and 5). For greater GSLs, mortality rates may have to exceed 20% in order for the SLP method to indicate stand loss. In the DPEAK 100, a mortality rate of 17% yields a static condition for 100 years (figure 3). Realistically, however, the existing GSL 40 stands will not be lost as the SLPs project unless the mortality continues. Instead they will continue to exist and grow, albeit at a rate unlikely to project them crossing the GSL 120 threshold in less than 100 years.

In contrast to the SLP estimates, the time estimates from GENGYM will underestimate the actual time needed to reach the susceptibility thresholds when substantial mortality occurs. While minimal mortality is incorporated in the GENGYM equations, that mortality is substantially less than the mortality observed in the BCRK, DPEAK and NSAV GSL 40s. Because abnormal mortality is not incorporated into the original stand data and the growth information is applied to the stand data as if no trees had died, the time estimates are much less than the time actually needed.

Neither method will provide an accurate estimate if a stand is subject to substantial mortality in the first 10 years and adjustments are not made. Because both methods were strongly influenced by the degree of mortality observed in this study, they may be applicable only to situations where mortality is limited to the death of a few trees from competition or endemic MPB populations. Even then, the loss of 1 ft^2 of BA to MPB populations in a GSL 80 stand may alter the SLP estimate for crossing the GSL 150 threshold by 4 to 6 years and the GENGYM estimate by 3 years (Obedzinski et al. 1999). However, endemic MPB mortality may not be as important in LP stands as windthrow, especially like the windthrow observed in some of our GSL 40s. In several GSLs, windthrow decreased the stocking level and created SLP estimates that suggest an ever decreasing BA. While windthrow may decrease the stocking level in the short term, it seems unlikely that this would continue as the SLP projection forecasts. At some point, the residual trees would become windfirm and BA would start to increase. Thus, the SLP estimates would be less realistic

than the GENGYM estimates. Until the influence of endemic MPB mortality and wind events are determined, forest managers should be cognizant that different stand growth scenarios can be derived from the two methods and both methods may provide inaccurate estimates if the stands are subject to substantial mortality soon after cutting.

In marking unmanaged stands to specific stand densities in preparation for partial cutting, spacing was one of several factors considered in the selection of leave trees. On some occasions, spacing was reduced in order to leave a more desirable tree. Thus, although spacing between leave trees was generally uniform throughout most of a stand, some higher density clumps may have existed. If tree selection tends to leave clumps of trees, pockets of greater tree densities embedded in otherwise relatively homogeneous stands may be problematic in the future. As long as average diameters remain below 8 to 9 inches, such stands may not be conducive to MPB infestation. As these stands develop, however, the susceptibility threshold may be exceeded within the pockets while most of the stand remains below the susceptibility threshold (i.e., a situation similar to the microcosm stands within unmanaged ponderosa pine stands as found by Olsen et al. 1996). As McGregor et al. (1987) noted, tree losses in partially cut stands were associated with unequal tree distributions, so relatively equal spacing needs to be maintained. Thus, managers should realize that the process of tree selection may create embedded pockets or microcosm stands of greater densities within a stand that may exhibit MPB infestations well before most of the stand reaches the susceptibility threshold.

In LP, large diameter trees are thought to be the first trees attacked by the MPB (Cole and Amman 1969) and are the most susceptible (Safranyik et al. 1974). If this is the case, then the susceptibility of the partially cut stands in this study may not have been altered substantially for the long term because larger diameter trees were generally retained as the residual trees while the smaller diameter trees were cut. As noted by McGregor et al. (1987), partial cutting may not be as effective in stands with many large diameter trees as in stands with smaller average diameters. If the MPB attacks these stands and kills a substantial portion of the trees in each stand regardless of its stand density, then partial cuts that favor larger diameter trees will not be a viable MPB management option for forest managers. If the MPB kills relatively few trees within the partially cut stands, then favoring large diameter trees in a partial cut is a viable option and the statement regarding beetle preference for large diameter trees may be applicable only when dealing with unmanaged stands.

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