AN ABSTRACT FOR THE THESIS OF

Teresa Lysak for the degree of Master of Science in Forest Science presented on July 31, 2000. Title: Hazard Rating System for Spruce Weevil (*Pissodes strobi*) in Sitka Spruce in the Northern Oregon Coast Range.

Abstract approved: Signature redacted for privacy.

Darrell W. Ross

The spruce weevil (*Pissodes strobi*) is a serious pest of Sitka spruce in Oregon. Weevils cause damage by killing the leader of a tree, resulting in defects such as crooks and forks that can render the tree unmerchantable. In this study, spruce stands 16-25 years old were surveyed for weevil damage. Trees had an average of 2.8 defects, ranging from 0 to 10, with minor crooks being the most common type of defect. More defects were seen in the upper portions of the trees than in the lower portions. Only 7% of the stands contained more than 200 undamaged trees per acre. The amount of damage was found to be positively correlated with distance from the ocean and growth rate and negatively correlated with elevation, latitude, and amount of spruce in the stand. These variables together explained 62% of the variation in amount of damage.

Hazard Rating System for Spruce Weevil (*Pissodes strobi*) in Sitka Spruce in the Northern Oregon Coast Range

by

Teresa Lysak

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented July 31, 2000
Commencement June 2001

Master of Science thesis of Teresa Lysak presented on July 31, 2000.

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ACKNOWLEDGEMENTS

I would like to thank Darrel Ross, my major professor, for all of his good help and advice. I would also like to thank Dave Overhulser, Oregon Department of Forestry, for helping set up the project and acquiring the funding, and Doug Maguire, Department of Forest Resources, Oregon State University, for his help determining the methods and analyses used. Thanks also to Steve Skinner, Astoria District, Oregon Department of Forestry; Keith Powell, Tillamook District, Oregon Department of Forestry; Thomas Parke, Willamette Industries, Inc.; John Washburn and Tim Tompkins, Simpson Timber Company; and Wayne Patterson, Hebo Ranger District, Siulslaw National Forest, for providing maps, stand data, and access to study sites.

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INTRODUCTION

Sitka spruce (*Picea sitchensis* (Bong.) Carr) is an important tree in the coastal Northwest. It is one of the fastest growing trees in North America (Harris 1990) and, along with its common associate western hemlock, comprises one of the most productive forest types in the world (Ruth and Harris 1979). Its wood is strong and light in weight and has been valued for a variety of specialty items, such as airplanes (Harris 1990). In addition to having desirable timber qualities, Sitka spruce also provides habitat for many wildlife species and fulfills a unique ecological role in the coastal environment. In spite of these good qualities, however, foresters seldom plant Sitka spruce in Oregon because of the damage that will be inflicted by the spruce weevil, *Pissodes strobi* Peck. Much of the land that was originally dominated by spruce has since been converted to stands of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) following logging or fire. Recently, however, there has been renewed interest in growing Sitka spruce. Swiss needle cast, a disease caused by a native fungus, *Phaeocryptopus gaumanni*, has become a severe problem in these Douglas-fir stands, causing many acres of young trees to almost cease growth. One of the options for dealing with this outbreak is to convert these stands to other species, namely hemlock and spruce. In addition to economic motives, there is also a desire to increase the diversity of managed forests in this area and to maintain them in a more natural condition. Sitka spruce was once a major component of the coastal forest and many agencies are interested in restoring it to its original status in the ecosystem.

To successfully grow spruce, a silvicultural system that accounts for the potential impact of the spruce weevil on tree survival and growth is required. This will likely result from an integrated plan that uses a combination of genetic, silivicultural, and chemical strategies for control (Alfaro et al. 1995). But at the foundation of any integrated protection plan, there needs to be an understanding of where and under what conditions weevils are most likely to be a problem. This study related the amount of weevil damage to different stand and environmental characteristics and documented the amount of damage that has occurred in northwest Oregon. The relationships identified were then used to develop a hazard rating model, which foresters can use to predict those areas and conditions under which the weevil is likely to cause the least amount of damage, and start to reintroduce this important species back into its native range.

LITERATURE REVIEW

The spruce weevil is a native pest found throughout North America, from the West Coast to the East Coast. It was originally divided into three separate species: the Sitka spruce weevil (*Pissodes sitchensis* Hopkins), the Engelmann spruce weevil (*Pissodes engelmannii* Hopkins), and the white pine weevil (*Pissodes strobi*), each named after its primary host. These three species are now considered to be ecotypes of the same species, *Pissodes strobi* Peck, though each ecotype still shows a strong preference for its particular host tree (Wallace and Sullivan 1985). Various common names have been used to refer to this weevil. Following the lead of McMullen (1976a), the name 'spruce weevil' will be used in this paper because it best describes the weevil's hosts in the Pacific Northwest.

Resource impact

Weevils lay their eggs on the leader of the tree, just below the current year's growth. After hatching, larvae feed on the phloem, moving downward in a continuous 'feeding ring'. This girdles and kills the leader, leaving a red, bent-over top that is easily identified in the field (Figure 1). Although the tree is never killed outright, death of the leader often causes forks and crooks, as one or more of the lateral shoots assumes dominance. If a tree is attacked repeatedly, it may become so deformed as to make it unmerchantable. Leader death also causes reduced height

Figure 1. Spruce weevil damage in late summer.

growth because it takes time for the new leader to assume dominance and because the lateral shoot that forms the new leader is usually shorter than the original leader. It is estimated that 60 to 70% of the annual height increment of the tree is lost each time it is weeviled (Gara et al. 1971, Patterson and Aizen 1989). In addition to causing a reduction in volume, this height loss can also cause the tree to become suppressed and killed by faster growing trees (Alfaro 1982, Patterson and Aizen 1989). The weevil usually attacks the fastest growing, tallest trees, making its impact especially serious.

The amount of damage in a plantation can be quite extensive. Reports of plantations in which over 90% of the trees have been infested are not uncommon (Alfaro 1982, Mitchell et al. 1990, Patterson and Aizen 1989, Graham 1918). In one report of plantations in the interior of British Columbia, none of the stands that had been planted in Sitka spruce developed into merchantable stands, and stands that were originally planted with a mixture of spruce and Douglas-fir had become almost pure Douglas-fir after fifty years (Alfaro 1982). In many of the coastal areas of British Columbia, plantations that were once Sitka spruce later had to be reclassified as a different vegetation type because most of the spruce had been attacked by the weevil and outcompeted by other vegetation (Hall 1994). No published reports have been made on the extent of weevil damage in Oregon, but the problem is serious enough that foresters in the area generally do not plant Sitka spruce.

Life history and population regulation

Spruce weevils emerge from hibernation in the spring, beginning around March or when temperatures reach between 45-60° F (Silver 1968, Wallace and Sullivan 1985). They feed by chewing a small hole in the bark of the tree and feeding on the inner bark in the area around the opening. Under optimum conditions, they will start to feed on the top of the previous year's leader and work their way downward as the season progresses. Eggs are laid in the phloem, in a similar pattern along the leader as occurs in feeding. The eggs take about 2 weeks to develop (Silver 1968). Upon hatching, the larvae remain in the leader, orienting downwards and eating the inner bark. In a successful attack, the larvae will form a continuous feeding ring inside the bark that will completely girdle the tree and kill any portions above where they are feeding.

After 5 to 6 weeks, the larvae pupate in the wood or the pith of the stem, in hollows called chip cocoons. Adults emerge from the end of August through November (Silver 1968). In most portions of their range, the weevils overwinter in the duff. In warmer areas such as Washington, weevils will often stay active during the winter, remaining on the bole or branches and feeding when the weather is warm enough (Gara et al. 1971). Weevils generally live for one year, though a few individuals may survive for up to four years (Wallace and Sullivan 1985).

Weevil populations are controlled primarily by climate and by the availability of suitable host trees (Alfaro 1994). Weevils tend to develop from *in situ* populations and do not form large outbreaks that spread across broad areas, as is common for some other insects (Alfaro 1994).

Host preferences

The spruce weevil is primarily a pest of young trees, with only certain tree heights and age classes at risk. Trees begin to be attacked when they reach about 4 ft in height. Weevil populations then increase rapidly, peaking when the trees are about 10 to 20 ft. After this, the population slowly declines until trees are between 40 and 50 ft tall, when it stabilizes at a very low level (Connola and Wixson 1963, Silver 1968, McMullen 1976a). This low population level usually corresponds to around 5% of the trees being attacked, a level which is considered to be endemic to natural stands (Alfaro 1994). This same population trend has also been measured in terms of tree age, with attacks beginning when trees reach about 5 years old and peaking when trees are between 10 and 15 years old. There is much variation in the age at which a low level of infestation is reached, varying from 16 years (Alfaro and Omule 1990, Mitchell et al. 1990) to 45 years (Alfaro 1994).

Once in an area, weevils do not randomly distribute throughout the stand, but instead tend to congregate preferentially on certain leaders. Within a stand, weevils prefer trees that are the fastest growing (Gara et al. 1971, Mitchell et al. 1990, Hall 1994), the tallest (Hall 1994), with the largest diameters (Patterson and Aizen 1989), and with the longest leaders (Wallace and Sullivan 1985, Alfaro 1989a). Leaders need to be a minimum of 4 mm in diameter, in order for the bark to be thick enough to accommodate eggs, with diameters between 8 and 11 mm being preferred (Sullivan 1961, Silver 1968). Leaders over 10 to 16 inches in length were also found to be necessary by some researchers (Silver 1968, Gara et al. 1971), though others have found overall leader length to have no correlation to the likelihood of attack (Sullivan 1961). Other characteristics such as the depth of resin ducts in the leader (Wallace and Sullivan 1985) and the proximity to another attacked tree (He and Alfaro 1997) were also found to be important.

Environmental preferences

Many characteristics of the surrounding environment, such as weather and soils, also have been found to influence weevil distribution. One important factor is temperature. The amount of cumulative heat necessary for oviposition has been quantified using a unit called a day-degree. Day-degrees are calculated by taking the average temperature for the day and subtracting from it a developmental threshold temperature, which in this case is 45°F. The values from consecutive days are then added together until the minimum amount of heat necessary for an event to occur is reached. In Sitka spruce, 1600 day-degrees (in °F) are required for weevil oviposition (McMullen 1976b). Based on weather data, McMullen (1976a) developed a map of areas on Vancouver Island where the day-degree requirements were not met and little weevil attack could be expected. This area turned out to be the northern tip of the island and a thin strip of land along the western coast, which corresponded well with actual attack records. This work was later modified, taking into account both the variation in temperatures over different years and also the differences between the temperature of the leader bark and the temperature of the air (Spittlehouse et al. 1994). Using temperature data from a region in eastern British Columbia, Spittlehouse et al. (1994) were able to successfully predict which biogeoclimatic subzones in the area were likely to have low levels of infestation.

Further south in Washington, temperature was not found to be a limiting factor (Overhulser and Gara 1981), although the area still showed the same pattern of attack as Vancouver Island, with attack levels being low along the coast and heavy inland. Instead of ovipositional activity, larval development was found to be limiting in coastal areas (Overhulser and Gara 1981). Inland trees were found to experience more moisture stress, which reduced their ability to produce resins that might kill the larvae (Warkentin et al. 1992). Based on vapor pressure deficit regimes, Warkentin et al. (1992) were able to predict which areas in western Washington would have low levels of attack.

Moisture regimes and soil drainage have also been examined, although on hosts other than Sitka spruce. On white spruce (*Picea glauca* (Moench) Voss) in the interior of British Columbia, it was found that those areas that received more moisture had a greater likelihood of being heavily attacked, probably due to faster tree growth (Taylor et al. 1991). Greater intensity of attack has also been found on imperfectly drained soils, both in eastern white pine (*Pinus strobus* L.) in New York (Conolla and Wixson 1963) and in Norway spruce (*Picea abies* (L.) Karst.) in Quebec (Lavellee et al. 1996).

Many site factors have been found to be uncorrelated to weevil attack, such as elevation (Connola and Wixson 1963, McMullen 1976a), aspect (Connola and Wixson 1963), depth of duff (Connola and Wixson 1963, Bellocq and Smith 1995), site quality (Taylor et al. 1991), and associated vegetation (McMullen 1976a).

Stand preferences

As early as the beginning of this century it was observed that fewer weevil attacks occur in shaded and in dense plantations (Graham 1918). Many authors have tested the effects of shade coming from various sources for its effects on spruce weevil attack. Shade from a hardwood overstory has been studied in white spruce (Taylor et al. 1996), eastern white pine (Sullivan 1961, Patterson and Aizen 1989), and Sitka spruce (McLean 1994) and has been found to reduce the number of weevil attacks in all cases. In studies with eastern white pine and white spruce, the percent of trees weeviled was reduced to less than 5% when the sunlight was reduced by 60-

80% (Sullivan 1961, Taylor et al. 1996). Even if insolation was reduced by only 25-50%, damage was still on the order of 10% of what it would have been in the open (Sullivan 1961). The correlation between shade and weevil attack is so well established in eastern white pine, that the degree of shade has been used by some researchers to predict the likelihood of weevil attack (Stiell and Berry 1985). In Sitka spruce plantations, however, observations have shown that even being completely enclosed in clumps of vine maple did not seem to prevent trees from being attacked (Alfaro 1982). One problem that has been found with the use of shade is that some attacks occur before the hardwood overstory has leafed out, making its presence ineffective. In the East, brushy species such as alder and willow were more effective in reducing attacks than taller species such as pine, cottonwood, and aspen, because the higher density of branches in the shrubby species reduced light more in the early spring (Taylor et al. 1996). Shade coming from the side has also been studied by cutting units in long rows of varying widths. This was found to be effective at widths 2/3 to 1 times the stand height. However, it was not as effective as overhead shade, probably because full sunlight was reaching the trees for at least part of the day and temperature was not reduced as much (Stiell and Berry 1985).

Tight spacing has also been found to be effective in reducing weevil damage. Heavily stocked Sitka spruce plantations were found to have a lower intensity of attack and better recovery from attack than lightly stocked stands. At a spacing of 9 ft, 35% of the crop trees had good form, versus 20% in the widest spacing of 15 ft (Alfaro and Omule 1990). Densely spaced trees can also play an important role in preventing competing vegetation from overtopping and suppressing the trees (Alfaro and Omule 1990).

Interplanting other conifer species with spruce has also been suggested, though no studies have been done to show its effectiveness. Alfaro (1982) found that plantations which were originally planted half in Douglas-fir and half in Sitka spruce were comprised of almost pure Douglas-fir 50 years later because the spruce had been suppressed and out-competed after being stunted by the weevil. This observation would make the effectiveness of this method questionable.

Stand characteristics that increase the population of predators could also impact weevil populations. In jack pine (*Pinus banksiana* Lamb.) in Ontario, shrews and mice were found to cause 5–13% mortality in weevils during the winter (Bellocq and Smith 1995). Any characteristics that would increase their populations could also decrease weevil populations.

Conclusion

The spruce weevil is a serious pest of Sitka spruce. Weevils kill the leader, deforming and stunting the tree. Although weevil infestation has been found in almost every Sitka spruce stand south of British Columbia, the amount of infestation has been shown to depend on certain characteristics of the site and stand. Using this knowledge, it has been possible, in other areas of North America, to predict those locations and conditions in which Sitka spruce is best able to grow. More information is now needed on how the weevil responds to the different conditions found in Oregon if Sitka spruce is to be effectively reintroduced back into this area.

RESEARCH DESIGN

Forty-one young Sitka spruce stands in the northern Oregon Coast Range were selected for study. In each stand, the amount of weevil damage present and various stand and environmental variables thought to influence weevil attack were measured. Regression analysis was used to identify which stand and environmental variables were related to amount of weevil damage. This information was then used to develop a model that could predict the amount of damage in a stand. The model applies to stands in the Oregon Coast Range that are north of Lincoln City, are between 16 and 25 years old, and contain more than 25% spruce.

METHODS

Site selection

All field sites were located in the Oregon Coast Range north of Lincoln City (Figure 2). Within this area, 41 different stands were selected for study, based on the following criteria. The stands had to be approximately 25 to 50 ft tall. In older stands, trees would be too tall for the top of the bole to be seen, while in younger stands, weevil attack would not yet have peaked. This generally corresponded to the stand being between 16 and 25 years old. Stands also had to be at least 25% spruce, be relatively uniform, and could not have been precommercially thinned. All stands that were found meeting these criteria were surveyed.

Field methods

In each stand, the amount of damage and each of the potential explanatory variables were determined. Two types of plots were used, those used to measure damage and those used to measure stand characteristics. Stands were sampled systematically. The distance between plots was determined by the size of the area sampled, which varied from 1 to 4 acres. No plots were located within 60 ft of the stand edge to avoid any edge effects, or in patches that were distinctly different from the rest of the stand.

Forty damage plots and five stand characteristic plots were sampled in each stand. At each damage plot, the spruce tree closest to the plot center was identified

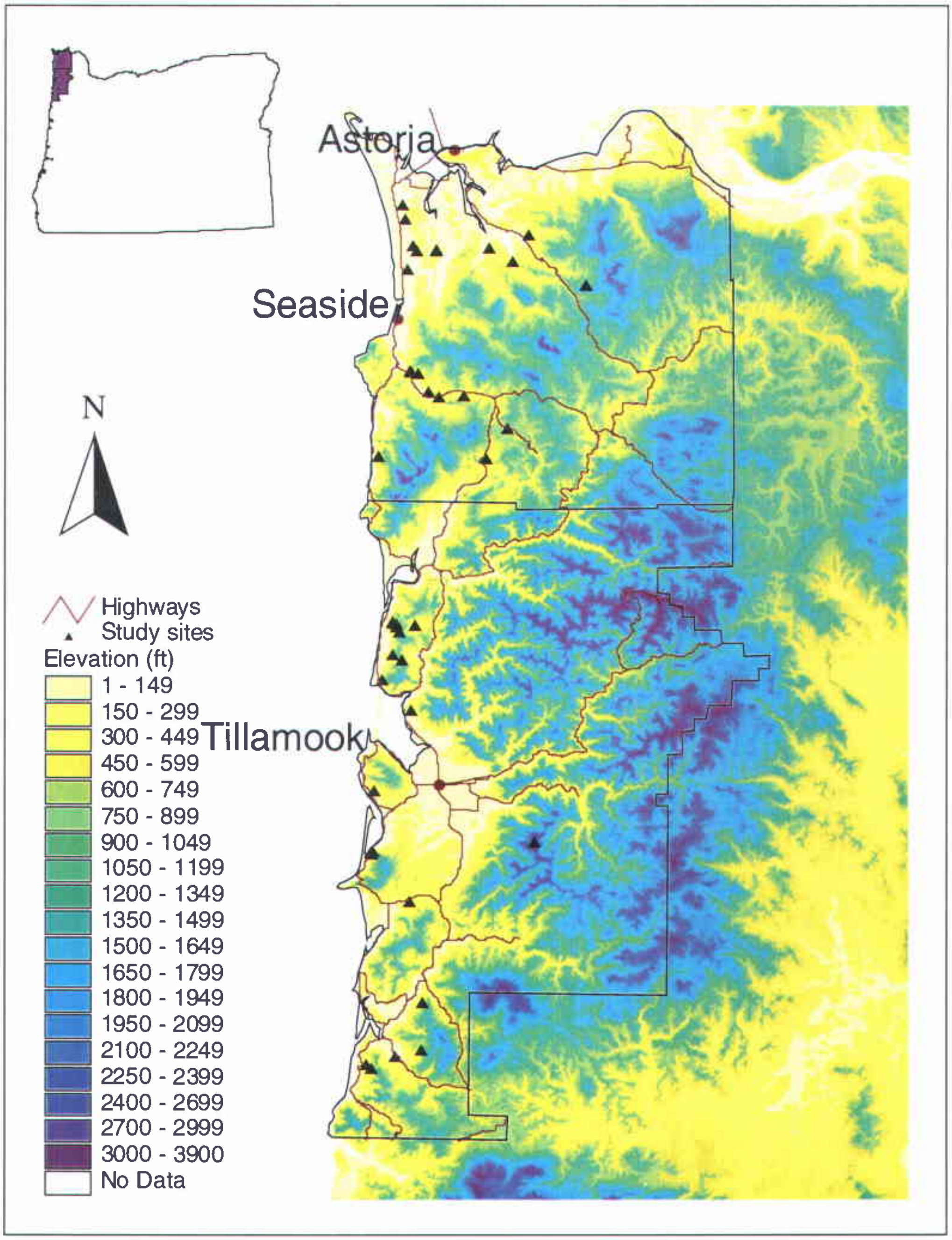


Figure 2. Study site locations.

and the damage in the tree recorded, as explained below. At every eighth damage plot, a fixed radius plot was established to determine stand characteristics. The center of the fixed radius plot was the spruce tree on which the damage measurements were collected. This method of locating the plot center was used to overcome problems associated with the patchy distribution of spruce in many of the stands, providing a better characterization of those areas where spruce was actually growing. The size of the fixed radius plots varied from 0.01 to 0.20 acre, based on a target of at least 10 spruce trees over 4 in diameter at breast height (4.5 ft, abbreviated dbh) per plot (Husch et al. 1987). Within each plot, the species and dbh of every tree was recorded, along with the heights of all conifers over 4 in dbh and the heights of all hardwoods over 1 in dbh. The largest diameter spruce tree in the plot was also bored to determine age and radial growth. In stands with a low percent spruce, two fixed radius plots of different sizes were used. A smaller plot was used for non-spruce trees, with the size chosen so that a minimum of 10 non-spruce trees over 4 in dbh would be sampled, while a larger sized plot was used to measure spruce trees. Information from the fixed radius plots was then used to calculate many of the explanatory variables.

Explanatory variables

Stand density. Several different expressions of stand density were calculated, since each measured something slightly different and there was no reason to assume that weevils were responding to any one particular aspect of stand density. Stand density was expressed as: trees per acre, trees per acre greater than 2 in dbh, basal area per acre (BA), volume per acre, and relative density (RD). Trees per acre greater than 2 in dbh was calculated in order to prevent seedlings and very young saplings from overly influencing stand density. Both BA and volume were included in spite of the fact that they are highly correlated, because BA is easier to accurately measure and would be preferred if it was sufficient to predict damage. Volumes were calculated using equations from Bell and Dillworth (1997, p. 379). RD was calculated by computing Reineke's stand density index (SDI) for each species ($SDI = TPA*(D_q/10)^{1.6}$), dividing the value by the SDI_{max} for that species, and summing the values for all species in the stand. SDI_{max} for spruce was derived from the stand density management diagram given in Peterson et al. (1997) and was calculated to be 780. SDI_{max} for red alder was 442 (Puettmann et al. 1993) and for Douglas-fir was 595.

Amount of spruce. The amount of spruce in the stand was also calculated in a number of different ways. These measurements were: number of spruce trees per acre, BA of spruce, and SDI of spruce.

Percent spruce. In addition to the total amount of spruce present, the relative amount of spruce was also thought to potentially be important. Percent spruce was calculated based by BA.

Growth rate. Measures of growth rate were: radial growth in the last 10 years, mean annual radial growth, mean annual volume growth per tree, and stand volume growth/year. Radial growth and volume growth per tree were both calculated from measurements taken on the largest spruce tree in each plot. Both radial and volume growths were used in order to account for the influence of weevil damage on height growth. Stand volume growth was calculated by dividing stand volume by stand age at breast height.

Temperature and humidity. It was beyond the scope of this study to measure these variables directly at the scale needed. However, a number of other factors which either influence or are influenced by temperature and humidity were measured instead. These included elevation, latitude, aspect, slope, distance from the ocean, amount of summer fog, plant association, and landform. Amount of summer fog was determined using a model developed by Chris Daly at the Department of Atmospheric Sciences, Oregon State University. An attempt was made to assign plant associations based either on the classification guide from the Siuslaw National Forest (Hemstrom and Logan 1986) or based on the most abundant understory species in the area. Neither of these methods worked well, since many of the stands were very dense and contained little understory and the classification guide was not designed to cover the whole extent of the study area. Because of these difficulties, plant association was broken down into only two categories, whether the stand contained more or less than 20% salal cover. Landform also was broken down into just two categories, whether or not the stand was located on a floodplain.

Hardwood shading. Each stand was rated subjectively according to whether or not it contained a hardwood overstory. To have a hardwood overstory, the stand had to have at least a third of the area covered by a hardwood canopy that was taller than the majority of the spruce and was likely to have been taller during most of the life of the spruce. Five out of the 41 stands met these criteria, though the amount of hardwoods varied significantly among these stands.

Age. Stand age was calculated from age measurements taken on the largest spruce tree in each plot.

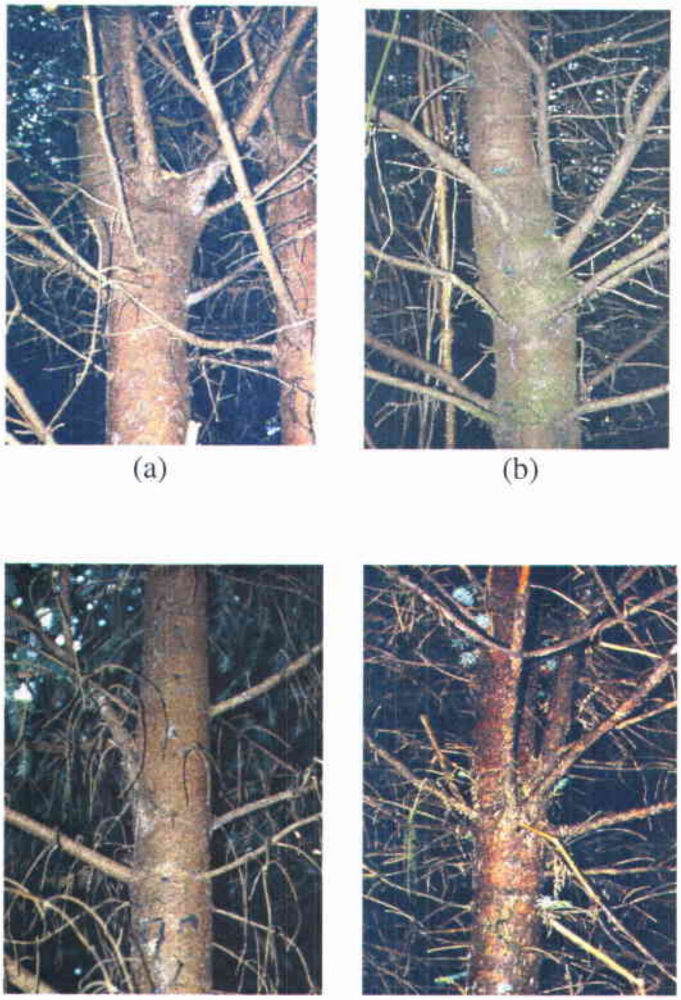
Measuring amount of damage

Amount of damage was chosen as the response variable instead of level of infestation, which is used in most hazard rating systems, because some of the stand characteristics, such as density, have been shown to influence not only how likely trees are to be attacked, but also how well they recover from weevil attack (Alfaro and Omule 1990). Looking directly at the amount of damage will account for both of these influences.

In order to easily compare the amount of damage in various stands, however, a single variable that could take into account different types of defects had to be developed. Following the lead of Alfaro (1989b), who worked with the spruce weevil in British Columbia, the types of defects seen in this study were divided into two categories, major defects and minor defects, with the overall rating for the tree based on the number of defects in each of these categories.

Major defects have a potentially large effect on the volume of wood harvested and include forks and major crooks (Figure 3). Major crooks, following the definition of Alfaro (1989b), were deflections in the bole that occurred at a branch node, in which the amount of deflection was more than 50% of the tree diameter at the base of the crook.

Minor defects primarily affect the quality of the wood and include minor crooks, ramicorn branches, scars, excessive branchiness, and sucker limbs (Figure 3). Minor crooks were those crooks in which the deflection was less than 50% of the



(a) (b)

(c) (d)

Figure 3. Types of defects caused by spruce weevil, (a) major crook, (b) minor crook, (c) ramicorn branch, and (d) fork.

tree diameter at the base of the crook (Alfaro 1989b), small enough to be covered over as the tree grows. Ramicorn branches were branches which came out of the bole at an angle of less than 45° and were less that half the diameter of the main stem. Scars were minor losses in the cylindricality of the stem (Alfaro 1989b), probably caused when a dead ramicorn branch broke off. In order to overcome the influence of stand density on branch size, excessive branchiness was considered to occur when the branches in a whorl were unusually large in size when compared to branches in other whorls in the same tree. Excessive branchiness was often accompanied by crooks or other defects. Sucker limbs were branches which came off the tree at a normal angle, but later bent upward to form a second leader. Sucker limbs were included as defects only when they were presumed to not be a result of an opening in the canopy.

Only one defect was tallied at each whorl, even though multiple defects often occurred together. In those cases, only the most severe defect was recorded. Seedlings and very young saplings that were obviously younger than the main cohort of trees were not used for measuring damage. Defects occurring on the bottom 3 ft of the bole were also not counted, since weevils do not attack trees that are this short (Connola and Wixson 1963, McMullen 1976a). Forks, however, were common at the base of trees. The top two whorls were also not counted because of the difficulty seeing them in most stands. In trees with forks, only the larger trunk was examined for defects.

In each tree that was examined for damage, the number and type of each defect in each 16 ft section of the bole was recorded and the dbh of the tree measured. The tree was then rated for amount of damage according to the following scale:

0 – no defect
1 – no major defects, 3 or fewer minor defects
2 – no major defects, minor defects greater than 3 but less than or equal to 6
3 – either one major defect or more than six minor defects
4 – 1 major defect, minor defects greater than 0 but less than or equal to 3
5 – 1 major defect, more than 3 minor defects
6 – 2 major defects, 0 or 1 minor defects
7 – 2 major defects, more than 1 minor defect
8 – 3 major defects, any amount of minor defects
9 – 4 or 5 major defects, any amount of minor defects
10 – more than 5 major defects, any amount of minor defects

The damage ratings for all of the trees sampled in a stand were averaged to get the damage rating for the stand.

Data analysis

In order to identify the stand and environmental characteristics that were most strongly correlated with amount of damage, the data were analyzed using multiple regression. First, in order to prevent an individual stand from having too much influence on the regression, the distribution of each variable throughout its range was examined and variables that were highly skewed or that contained outliers were transformed. Aspect also had to be transformed to a linear function. This was done in two different ways. First, aspect and slope were transformed together, following the guidelines given by Stage (1976). Using amount of damage as the response variable, the reference aspect calculated by this method was 50°, indicating that damage peaked on southwest aspects and was least severe on northeast aspects. Since southwest aspects are likely to be the most droughty, this reference aspect makes biological sense. Aspect was also transformed without considering slope by taking the cosine of the aspect, again using 50° as the reference aspect (Beers et al. 1966). In this transformation, flat sites were assigned an intermediate position (Stage 1976).

Multiple regression was then performed under an all subsets algorithm, with damage as the response variable and each of the stand and environmental variables as the explanatory variables. Adjusted R^2 was used to select a set of potentially good models. Since many of the explanatory variables measured similar attributes and consequently were highly correlated, the stipulation was added that the models could not contain more than one variable from each of the following categories: stand density, amount of spruce, growth rate, aspect, and a fifth category containing distance from the ocean and amount of summer fog. Models that contained more than one variable from each category were eliminated. Models whose variables were not all statistically significant (all $P \leq 0.10$) were also rejected. Because the adjusted R^2 method is biased towards models with large numbers of explanatory variables, Mallow's Cp statistic and the Bayesian Information Criteria (BIC) were also examined. These statistics were calculated from a model search that contained only one variable from each category, since they are affected by the presence of highly correlated explanatory variables, so only certain subsets of the models could be compared with each other using these statistics. Partial residual plots of all of the variables in the best models were then examined to check the adequacy of the transformations and to see if the results were being overly influenced by just a few stands. Cook's Distance, studentized residuals, and leverages were also computed to examine the influence of individual stands.

RESULTS AND DISCUSSION

Stand descriptions

The stands surveyed for this study represent a wide variety of tree densities and species compositions, as well as cover a wide range in elevation, distance from the ocean, and aspect (Table 1). Since the stands encompass most of the conditions likely to be encountered, the results of this study should be applicable to all spruce stands within the geographic and age range covered by the study.

Because the stand variables given in Table 1 were calculated using different plots than the plots that were used to measure damage, the mean relative diameter for each stand (average diameter of the trees on which damage measurements were taken divided by the average diameter of the stand as calculated from the fixed radius plots) was calculated to determine if any bias occurred in the selection of the damage trees. Mean relative diameters ranged from 0.95 to 1.27, with an average of 1.08, indicating that the trees on which damage was recorded were slightly larger than the stand average. This is consistent with the fact that seedlings and very small saplings, which were younger than the main cohort of trees, were not used for measuring damage.

Table 1. Median, maximum, and minimum values of various stand characteristics. All variables were calculated on a stand level.

	Median	Maximum	Minimum
Tree size:			
Dbh of spruce (in)	7.47	10.94	4.79
Dbh of other conifers (in)	5.48	9.05	1.61
Height of spruce (ft)	36.15	51.16	22.08
Height of other conifers (ft)	41.03	66.33	20.0
Relative height of other conifers (ht other conifers/ ht spruce)	1.15	1.92	0.66
Relative height of hardwoods (ht hardwoods/ ht spruce)	1.08	1.95	0.64
Stand density:			
BA (sq ft/acre)	190	315	91
Trees/acre	784	2076	386
Volume (cu ft/acre)	3164	6889	1209
Relative density	0.595	0.868	0.257
Stand composition:			
% spruce (by basal area)	75.4	98.8	21.1
% hemlock	9.65	54.89	0
% Douglas-fir	0	50.61	0
% alder	3.75	48.42	0
% other hardwood	0	10.12	0
BA of spruce (sq ft/acre)	140.2	311.5	32.1
Growth rate:			
Mean annual radial growth (in/yr)	0.326	0.461	0.179
Mean annual volume growth per tree (cu in/yr)	0.770	1.573	0.229
Mean annual stand volume growth (cu in/yr)	201.2	318.9	68.7
Distance from ocean (mi)	2.74	15.7	0.568
Elevation (ft)	290	2720	50
Latitude (degrees)	45.64	46.12	45.13
Age at breast height	16.8	29.8	11.4

Amount of damage

Of all the trees surveyed, the number of defects per tree averaged 2.8, ranging from 0 to 10. This corresponds to one visible attack every 5.6 years (average stand age at breast height divided by average number of defects per tree). When the number of defects per tree was calculated for each stand as a whole, stands averaged from 1.0 to 5.2 defects per tree.

Damage ratings on individual trees ranged from 0 to 9, while stand averages ranged from 1.3 to 6.5 with a median of 3.5. The distribution of average stand damage ratings was reasonably normal except for being truncated on the lower end.

A rough estimate of the percent of trees attacked per year, calculated by dividing the average number of defects per tree by the stand age at breast height (since defects below 3 ft were not counted), was 18%, ranging from 5 to 35%. In addition to inaccuracies stemming from other assumptions, this calculation gives a low estimate because it considers only those attacks that result in visible symptoms. Alfaro (1989b) found that 36% of all attacks resulted in no visible sign of damage. Using this factor to correct the attack estimates yields attack levels of 8 to 55%, similar or slightly higher than has been seen in other studies (Alfaro and Omule 1990, Mitchell et al. 1990).

Type of damage present

Of all the defects observed, minor crooks were the most common, having been present 50% of the time (Table 2). Crooks, however, were often accompanied by ramicorn branches or other defects. Since only one defect was recorded at each node and crooks were given preference over other minor defects, the presence of these other defects is underrepresented in this table.

Table 2. Percent of the total number of defects caused by the spruce weevil in each category.

	Forks	Major crooks	Minor crooks	Ramicorn branches*	Scars **	Branchiness ***	Sucker-limbs ***
Percent of all observed defects	10.1	23.9	50.0	11.2	3.8	0.6	0.3
SD	4.4	7.0	8.9	6.2	4.4	0.8	1.5

*unaccompanied by a crook, fork, or scar
**unaccompanied by crook or fork
***unaccompanied by another defect

Number of undamaged trees in a stand

Thirty-one stands, or 76%, had at least some trees that were undamaged by the weevil. However, the total number of undamaged trees in most stands was small, with only 7% of the stands having more than 200 undamaged trees per acre (Figure 4). If trees with a damage rating of 1 (1 to 3 minor defects and no major defects) are also considered to be acceptable, then the number of acceptable trees per acre becomes much higher, with 29% of the stands having more than 200 acceptable trees per acre (Figure 5).

The number of acceptable trees per acre was reasonably well correlated with stand density (r = 0.57). Because of this, the percent of trees in a stand that were undamaged and the percent of trees that were acceptable were also examined. Only 15% of the stands had more than 25% of their trees undamaged (Figure 6), while 63% of the stands had more than 25% of their trees with a damage rating of greater than 1 (Figure 7). The best stand had only 42% of its trees undamaged (Figure 6). Both the percent of acceptable trees and the number of acceptable trees per acre increased as damage decreased (r = 0.96 and 0.81 respectively).

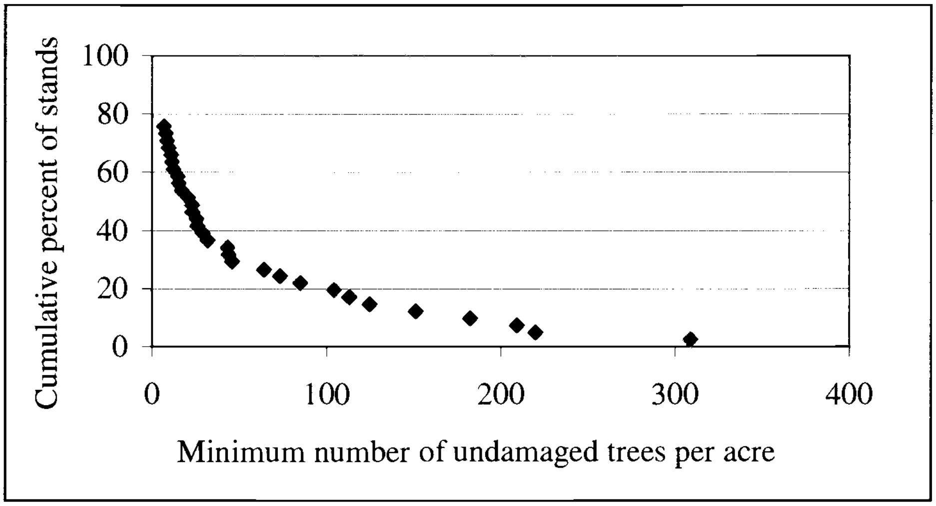


Figure 4: Cumulative percent of stands versus trees per acre in each stand that were undamaged by spruce weevil.

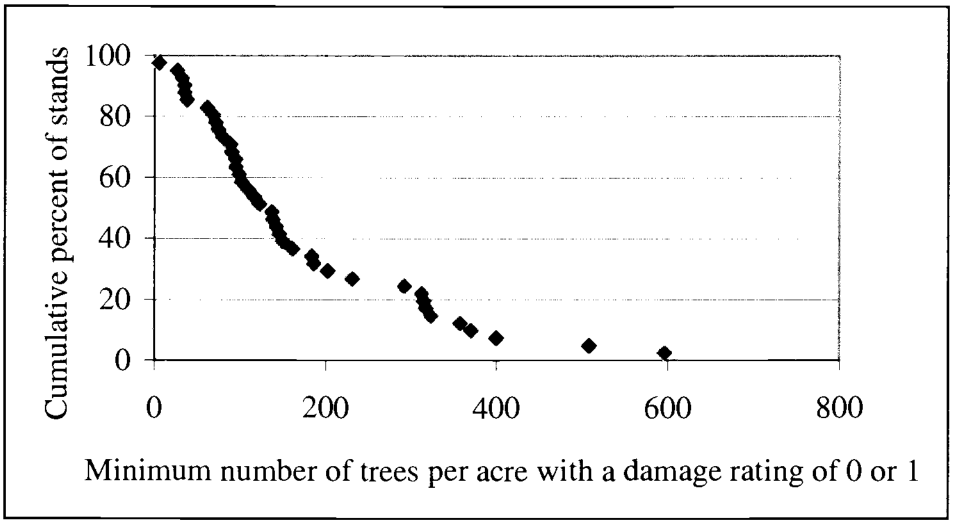


Figure 5: Cumulative percent of stands versus trees per acre in each stand with a damage rating of 0 or 1. Trees with a damage rating of 0 or 1 contain up to 3 minor defects and no major defects that were caused by spruce weevil.

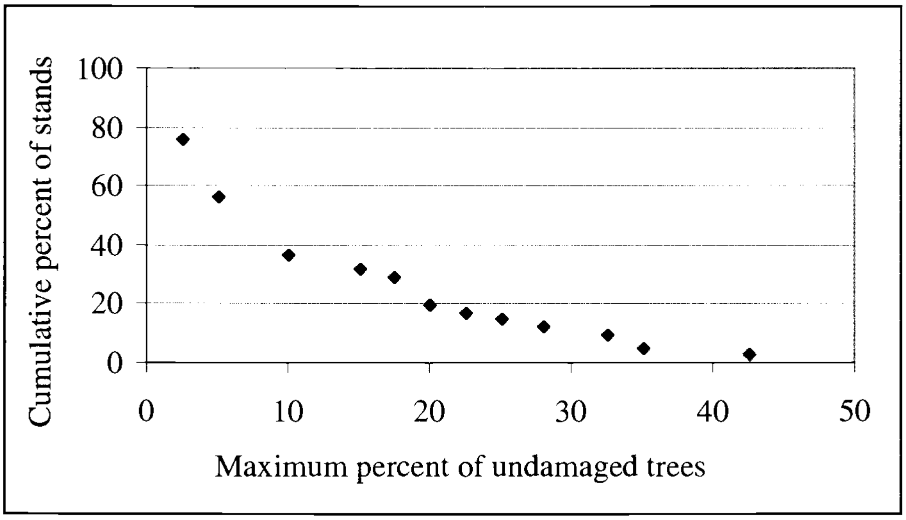


Figure 6: Cumulative percent of stands versus percent of spruce in each stand that were undamaged by spruce weevil.

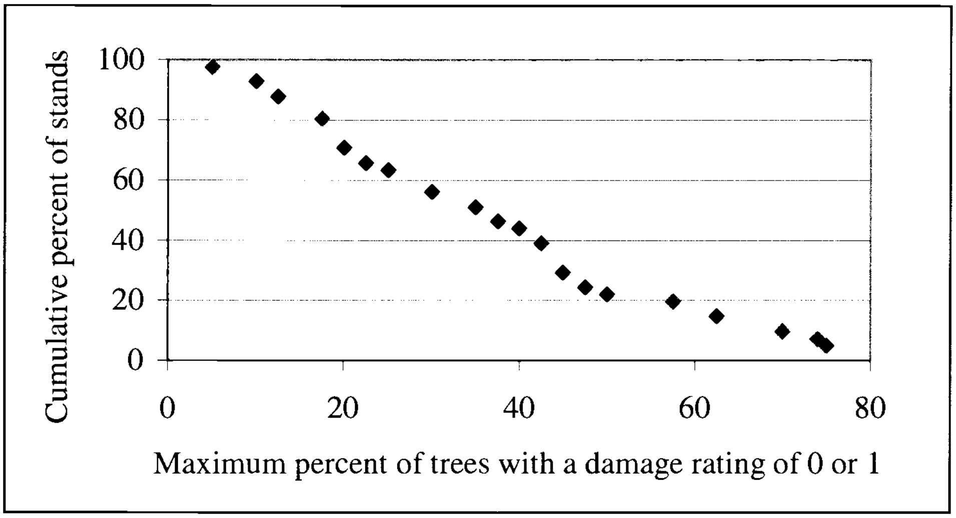


Figure 7: Cumulative percent of stands versus percent of spruce in each stand with a damage rating of 0 or 1. Trees with a damage rating of 0 or 1 contain up to 3 minor defects and no major defects that were caused by spruce weevil.

Amount of damage versus height on tree

More defects were found on the higher portions of the trees. In those stands that averaged more than 38 ft tall, the percent of defects occurring in the bottom 16 ft of the boles was compared to the percent found in the 16 to 32 ft sections. Stands had an average of 33% of the defects in the lower 16 ft, ranging from 23 to 48%, and only 5% of the major defects occurring in the lower portions of the tree, ranging from 0 to 18%. Since the lower portion of the bole is the most valuable, this indicates that high levels of damage do not necessarily imply low merchantability.

The distribution of defects within the tree is not satisfactorily explained by the hypothesis that different amounts of weevil attack have occurred at different heights. Weevil attack has been shown to peak when the tree is between 10 and 20 ft tall (Connola and Wixson 1963, McMullen 1976a), a range which is fairly evenly divided between the two categories. Weevil attack has also been shown to peak when the stand is between the ages of 10 and 15 (Alfaro and Omule 1990, Mitchell et al. 1990). Since the average age of these stands is roughly 24, the age range of peak attack is also fairly evenly divided between the two categories and suggests that equal amount of defects should occur in each of the two sections of bole. The distribution that was found, instead, seems to suggest that the defects in the lower bole have healed over time.

Height loss

In addition to form defects, weevil damage also causes reduced height growth (Alfaro 1982, Patterson and Aizen 1989), since one year's worth of growth is killed with each attack. This may potentially lead to the spruce being eliminated by overtopping and suppression in those stands that contain a high percentage of other conifers. Although observations tended to confirm this, the effect is difficult to quantify because of the lack of weevil-free stands for comparison. A strong correlation, however, was found between the relative height of spruce (the average height of the other conifers divided by the average height of the spruce) and damage rating ($P = 0.0001$, $R^2 = 0.49$).

Height loss was not reflected in the height:diameter ratio of the spruce. Assuming that overall growth rate is not seriously affected by weevil damage, it would be expected that damaged trees, whose height growth was curtailed, would compensate by growing larger in diameter. There was no evidence of a relationship, however, between the average height:diameter ratio of a stand and the damage rating, even after the effect of stand density was accounted for ($P = 0.81$).

Amount of damage versus tree size

One silvicultural strategy that has been suggested as a way to reduce weevil damage is to establish stands at a very high density and thin after a good quality first log has developed (Stiell 1979, Alfaro and Omule 1990). The timing of the thinning is important and will depend in part on what crown class tends to have the highest amount of damage. To ascertain this, the correlation between height of individual trees and their damage rating was examined. Because only five trees per stand were measured for both damage and height, all trees that had both measurements were examined together, regardless of which stand they came from. Very little correlation was found between height and damage ($r = 0.16$), although there was statistical evidence of a negative relationship ($P = 0.03$) resulting from the very large sample size ($n = 205$). The correlation between the diameter of individual trees and their damage rating was also examined for each stand individually. Although some stands showed evidence of a relationship between diameter and amount of damage (lowest P for all the stands was 0.009), the direction of the relationship was not consistent among the stands and the amount of variation explained by the relationship was very low (highest R^2 for all the stands was 0.17). These findings are different than the results of previous studies, which found that the smaller trees in the stand had less weevil damage (Stiell 1979).

Predicting damage

Amount of damage, as quantified by the damage rating, was found to be correlated with elevation, distance from the ocean, amount of spruce, and growth rate. Several models emerged, with different levels of certainty. Table 3 contains a list of models and predictive factors. Actual regression equations are presented in Appendix 1.

Over half of the variation in damage can be explained using just 3 variables: elevation, distance from the ocean, and latitude. All of these variables were highly significant in the model (all $P \leq 0.0003$). Damage was positively correlated with the log of distance from the ocean and negatively correlated with the square root of elevation and with latitude. The relationship with distance from the ocean is consistent with findings in other locations and is probably the result of higher summer humidity levels along the coast. Higher humidity levels reduce the amount of moisture stress in the spruce, enabling the trees to better defend themselves and pitch-out weevils (Warkentin et al. 1992). The correlation between distance from the ocean and predicted amount of summer fog was very high ($r = 0.85$). The relationship between damage and elevation may be due either to the effect of elevation on temperature or to its effect on the amount of cloud interception. The mechanisms by which temperature influences weevil damage in Oregon, however, will be much different than in British Columbia, where it has been an important factor in other hazard rating systems. Temperatures in Washington were found to be too warm to limit weevil development like they do further north (Overhulser and Gara 1981) and this is likely to hold true in Oregon as well. The influence of temperature may be the result of its effect on the level of moisture stress in spruce during the summer. Although it might be expected that elevation would increase as one moves farther inland, the correlation between elevation and distance from the ocean was actually quite small ($r = 0.12$) and should not create problems for predictions based on the model (Figure 2). Correlations between elevation and latitude and between distance from the ocean and latitude were higher ($r = 0.35$ and 0.33 respectively). Latitude may be important in the model because of its influence on temperature, but its effect may also be due to differences in geology or weather patterns as one moves from north to south (Hemstrom and Logan 1986).

A more complete model also included the variables mean annual rate of volume growth per tree and amount of spruce in the stand. Damage was positively correlated with growth rate and negatively correlated with amount of spruce, a finding consistent with previous studies (Sullivan 1961, Gara et al. 1971, Alfaro 1989a, Alfaro and Omule 1990, Mitchell et al. 1990). The significance of each of the variables in the best five variable model was much less than in the three variable model (all $P \leq 0.064$). However, all variables were still statistically significant and both the Cp and BIC statistics indicated that this model was better than the three variable model. Both growth rate and amount of spruce had outliers in their population distributions, a situation which can potentially invalidate predictions based on a regression model. None of the case influence statistics, however, suggested that this was occurring.

Several measures of amount of spruce produced good five variable models. The measure that yielded the highest level of significance for each of the variables in the model was SDI of spruce. However, when BA of spruce or percent spruce were substituted, the significance of each of the variables in the models did not decrease substantially (all $P \leq 0.064$, 0.077, and 0.096 for respective models). The model containing percent spruce had the greatest explanatory power, though the explanatory power of all of the models were similar ($R^2 = 0.602$, 0.598, and 0.605 for respective models). Since all of these measures of amount of spruce produced good models, the important factor is probably the total amount of spruce present and not its relative abundance in relation to other tree species. For this reason, as well as the higher significance of the variables, SDI of spruce, a measure of density that accounts for the differences in average tree size among the stands, was used in the final model. Although stand density was not included in any of the models, SDI and BA of spruce were both highly correlated with the corresponding measures of stand density.

There are several variables that, by themselves, can be used as very general predictors of the amount of damage. Damage was higher in stands on floodplains and was lower on sites that had a salal cover greater than 20% (Table 3). These variables did not show up in any of the more complex models because they were also related to elevation and distance from the ocean. Elevation, by itself, also accounted for almost 20% of the variation in damage (Table 3).

Table 3. Summary of different regression models used to predict amount of spruce weevil damage in Sitka spruce in northwest Oregon.

Variables included in model	R^2	Highest p-value of each of the explanatory variables
-Floodplain	0.19	0.005
-Square root of elevation (ft)	0.18	0.006
-Salal cover >20%	0.17	0.008
-Log of distance from ocean (mi) -Square root of elevation (ft) -Latitude (degrees)	0.522	0.0003
-Log of distance from ocean (mi) -Square root of elevation (ft) -Latitude (degrees) -SDI of spruce (inches, acres) -Mean annual rate of volume growth/tree (cu in/yr)	0.602	0.064

Not all variables have equal importance in predicting the amount of damage likely to occur in a stand. The importance of each variable in the five variable model was calculated by taking the difference between the high and low values for the variable and multiplying it by the coefficient given by the regression equation. This importance is relative to the rating scale, which ranges from 0 to10. The values are given in Table 4.

Table 4. Importance of each variable on predicted amount of spruce weevil damage. Calculated by multiplying the difference between the high and low values for the variable by the coefficient given by the regression equation.

	Square root of elevation	Log of distance from ocean	Latitude	Growth rate	SDI of spruce
Coefficient	-0.0880	0.6834	-1.8796	1.0972	-0.0019
Potential amount of influence on damage rating	3.90	1.09	2.11	1.56	1.17

Hazard rating model

The amount of damage likely to occur in a stand can be calculated by adding the following components.

Elevation:

square root of elevation (in feet) x -0.09 = ___________

Distance from the ocean:

log of distance from the ocean (in miles) x 0.76 = ___________

Latitude:

latitude (in degrees and minutes) x –2.11 = ___________

This ranges from 45.13 to 46.12 in northern Oregon.

SDI of spruce:

spruce trees/acre x $(D_q/10)^{1.6}$ (in acres and inches) x –0.002 = ___________

D_q is the quadratic mean diameter.

Growth rate:

mean annual rate of volume
growth in larger trees (in cubic inches/year) x 1.10 = ___________

This ranges from 0.23 to 1.57 in the stands in this study.

\+ 94.53

=

The rating ranges from 0 to 10, with 0 representing no damage and 10 representing the highest amount of damage. This model applies to stands in the Oregon Coast Range north of Lincoln City that are between 16 and 25 years old and contain more than 25% spruce.

CONCLUSION

Amount of damage versus frequency of weevil attack

In this hazard rating model, amount of damage caused by the spruce weevil was used as the response variable in place of frequency of weevil attack. Although the two are related, there are many other factors besides frequency of attack that affect how much damage occurs. Amount of damage is also influenced by the likelihood that the attack will generate a defect, how defects may heal over time, the stand age at which weevil populations naturally start to decline, and how attack rate may change from year to year. The first three of these factors are, to some extent, also influenced by the same stand characteristics that affect the rate of attack. The likelihood that the attack will generate a defect has been shown to be influenced by stand density (Alfaro and Omule 1990). How fast trees are able to heal over a defect depends on how fast they are able to put on new wood, which is related to growth rate. The stand age at which weevil populations naturally reach a low level has been shown to range from 15 years (Alfaro and Omule 1990, Mitchell et al. 1990) to 45 years (Alfaro 1994) and is thought to depend on the changes in microclimate that occur as the stand ages (Alfaro and Omule 1990). How rapidly these changes occur can vary depending on stand density. Assuming that bole damage is more important than actual rate of attack, looking directly at amount of damage is one way to incorporate all these influences.

If attack rate changes substantially from year to year, however, this could confound the results of this study. One study did find synchronous annual variation in attack rates among three different stands, with the variation being on the order of 10 to 15% of the trees in a stand. Since the maximum frequency of attack in a stand was only around 50%, this represents a substantial amount of variation (Alfaro and Omule 1990).

Implications for silvilculture of Sitka spruce

Although the data from this study seem to indicate that density of spruce is more important in predicting the amount of weevil damage than either total stand density or percent spruce, the effects of each of these variables are difficult to separate out because of the high degree of correlation between them. Amount of spruce is highly correlated with both percent spruce and stand density, though percent spruce and stand density are not themselves correlated (Table 5). Previous

Table 5. Correlation coefficients (r) for several of the explanatory variables measuring amount of spruce, stand density, and percent spruce.

	SDI of spruce	BA of spruce	BA	RD	stand volume
% spruce	0.74	0.72	0.32	0.03	0.24
SDI of spruce	--	0.97	0.84	0.66	0.77
BA of spruce	--	--	0.87	0.62	0.81
BA	--	--	--	0.86	0.96

studies examining the effect of density have been done in stands of pure Sitka spruce and have hypothesized that the decrease in damage found in denser stands is due either to tighter spacing causing fewer attacks to result in bole damage, or to the higher growth rate associated with low density causing trees to be able to be attacked again sooner (Alfaro and Omule 1990). Neither of these mechanisms should depend on the species make-up of the stand. The results of this study, however, seem at first to indicate that density of spruce is important, while total stand density is not. If this is true, then a different mechanism would have to be proposed. It is quite possible, however, that both variables are important and that the inflated variance that occurs when two explanatory variables are highly correlated may be preventing them from both occurring together in any good model.

Percent spruce was included as an explanatory variable to discover if the degree of interspersion of the spruce among other trees, which might also represent an interaction of amount of spruce and stand density, was important. Percent spruce did appear in a good five variable model. However, since percent of spruce is highly correlated with total amount of spruce (Table 5), its inclusion in the model could indicate the importance either of interspersion or of total amount of spruce. Again, the fact that the two variables never appear together in a model might be due to inflated variance, making it difficult to separate out the influence of each factor.

Separating out these factors becomes important if the management objective is to create a high level of diversity in a stand, as is becoming common on public lands. If amount of spruce is indeed the variable that is important in predicting amount of weevil damage, then creating a multi-species stand, which would contain fewer spruce trees than would a pure stand, will cause there to be more attack per tree. However, before this conclusion is reached, more work should be done to try and separate out the influences of spruce density, total stand density, and degree of interspersion of the spruce.

Factors influencing growth rate

The explanatory variable growth rate was measured in three different ways. The measures that appeared in good models were mean annual volume growth per tree and mean annual radial growth, while stand volume growth per year did not. Neither radial growth nor volume growth per tree were highly correlated with stand density ($r = 0.29$ and 0.46 respectively), with volume growth per tree actually increasing as stand density increased. This indicates that the stands have not yet reached the point where the growth rate of individual trees is reduced through competition, implying that their growth rate is being influenced more by site quality than by stand density. If it had been possible to determine site index for the stands, this probably would have proved to be an important explanatory variable.

Genetic resistance

Sitka spruce from different localities have different amounts of resistance to spruce weevil and much work has been done trying to identify resistant varieties (Mitchell et al. 1990, Alfaro et al. 1995). No evidence was seen in this study of any locations that had more resistance than would be expected; but since the aim of the study was to identify the amount of attack likely to be expected under given conditions, it would be difficult to identify outliers at the same time. If some of the stands were substantially more genetically resistant, this could potentially confound the results of the study.

Studies in other locations have also identified individual trees within a stand that had unusually good growth and form, indicating resistance (Alfaro 1982). No such trees were seen in any of the stands examined as part of this study.

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APPENDIX

The following regression equations were developed to predict the amount of damage caused by spruce weevil in Sitka spruce in northwest Oregon. Amount of damage was quantified using a damage rating which ranged from 0 to 10.

5 variable model:

damage = 94.5338 + 0.7578 log of distance from the ocean (in miles) – 0.0866 square root of elevation (in feet) – 2.1136 latitude (in degrees) – 0.0022 SDI-spruce (in acres and inches) + 1.1588 mean annual rate of volume growth/ tree (in cubic inches/year)

3 variable model:

damage = 95.4308 – 0.0929 square root of elevation (in feet) + 0.8378 log of distance from the ocean (in miles) – 2.1418 latitude (in degrees)

1 variable models:

damage = 1.19160 + 1.4217 floodplain
where floodplain = 1 if stand does not occur on a floodplain
floodplain = 2 if stand does occur on a floodplain

damage = 4.9138 – 0.0603 square root of elevation (in feet)

damage = 1.5996 + 1.2344 plant
where plant = 1 if salal cover > 20%
plant = 2 if salal cover < 20%