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Evaluation of post harvest conditions contributing to attacks by the red turpentine beetle, Dendroctonus valens LeConte at the Massabesic Experimental Forest in southern Maine

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EVALUATION OF POST HARVEST CONDITIONS CONTRIBUTING TO ATTACKS BY THE RED TURPENTINE BEETLE, *DENDROCTONUS VALENS* LECONTE AT THE MASSABESIC EXPERIMENTAL FOREST IN SOUTHERN MAINE

BY

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DEDICATION

This thesis is dedicated to my mother.

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Silvicultural management of *Pinus strobus* L. runs the risk of damaging residual trees and can increase the probability of attack from damaging insects, including the common bark beetle *Dendroctonus valens* Le Conte. Considered a secondary pest, it is possible that *D. valens* is capable of economic impacts such as the downgrading of logs and lumber due to defect and blue-stain. To assess post harvest conditions that contribute to the probability and severity of *D. valens* attacks in *Pinus strobus*, stand and tree characteristics were sampled in four silvicultural treatments and one control site in southern Maine. Results showed that clearcuts were least likely to have attacks. Additionally, increases in residual pine and hardwood basal area reduce the probability of attack, while increases in height and logging damage increase the probability of attack. Increased basal area of *Pinus strobus* stumps was shown to play the greatest role in severity of attack.

INTRODUCTION

DENDROCTONUS AS A GENUS

The genus *Dendroctonus* Erichson, known as the tree killers contains 19 species, 17 of which are indigenous to North and Central America (Wood 1982). Additionally, one other species is native to northern Europe and Asia and another is native to China (Wood 1982).With a range from Arctic North America to northwest Nicaragua, the beetles within the genus *Dendroctonus* are considered to be some of the most destructive pests in the coniferous forests of the Americas (Hopkins 1909; Wood 1963; Wood 1982). Economic costs of infestation are associated with the loss of millions of board feet of lumber volume and damage to commercial forests from species such as *D. brevicomis* Hopkins (western pine beetle) (Miller and Keen 1960), *D. frontalis* Zimmermann (southern pine beetle) (Thatcher and Barry 1982) *D. rufipennis* Kirby (spruce beetle) (Holsten et al 1999) and *D. ponderosae* Hopkins (mountain pine beetle) (Gibson et al 2009). Other impacts caused by *Dendroctonus* spp. are degradation of residential property values and costs to restoration programs (Price et al. 2010), and control efforts and monetary losses in recreational areas (Stark and Cobb 1969; Leuschner and Young 1978), as well as reductions in scenic beauty (Buhyoff et al. 1982). The possibility of damaging and complex interactions with forest fire (Lynch et al. 2006; Jenkins et al. 2008) is also a possibility. Following a bark beetle outbreak, ecological effects can include increases in stream flow due to death of forest trees (Bethlahmy 1974), losses in plant diversity (Holsten et al. 1995), variation in stand structure and future increases in tree vigor and growth due to the availability of resources (Romme, et al. 1986). Increases and simultaneous decreases in various avian species can also be expected (Martin et al. 2006) with positive effects for species diversity in some woodpeckers (Drever and Martin 2010) and songbirds (Lance and Howell 2000).

In general, *Dendroctonus* spp. are found attacking trees that are weakened or stressed in some manner. Some species will attack apparently healthy trees (Hopkins 1909; Wood 1963). Species such as *D. adjunctus* Blandford, *D. frontalis,* and *D. ponderosae* attack the main trunk (Hopkins 1909; Wood 1963, Wood 1982; Massey et al 1977; Paine et al. 1981), while still others such as *D. terebrans* (Olivier) and *D. valens* LeConte prefer the lower bole and stump (Hopkins 1909; Wood 1963, Wood 1982). This genus is typically split into two general categories, differentiated by their attack habits. Less aggressive, or secondary species such as *D. terebrans, D. valens and D. micans* (Kugelann) tend to attack in a less aggregated fashion, attacking but on occasion killing stressed and weak trees. Other more aggressive, primary species of *Dendroctonus* such as *D. brevicomis, D. frontalis* and *D. ponderosae* mass attack in an aggregated fashion killing apparently healthy trees (Hopkins 1909; Wood 1963; Wood 1982; Bevan and King 1983; King and Fielding 1989; Raffa et al.1993; Paine et al. 1997). Under ideal conditions and epidemic population levels any of these species can behave as a primary tree killer.

The *Dendroctonus* female first locates and enters a potential host tree and is shortly joined by a male. Most species such as *D. frontalis* (Payne 1975; Payne 1978; Pureswaran et al. 2004), *D. pseudotsugae* (Wood 1982; Pureswaran et al. 2004) and *D. terebrans* (Hopkins, 1909; Smith 1963a; Payne et al. 1987) cue on a combination of aggregation pheromones and host volatiles, while other species such as *D. valens* are mainly attracted to host volatiles (Hobson et al. 1993; Sun et al. 2004; Erbilgin et al. 2007). These chemicals are the mechanism for mass attack (Rudinsky 1962; Wood 1982). Females may leave the tree to start another gallery after laying eggs in the first and it has been observed that although typically monogamous, some male *Dendroctonus* spp. may leave the gallery after mating to find another female (Wood 1982). Evidence of tree attack by *Dendroctonus* spp. can be observed in the form of pitch tubes on the trunk or stump, red boring dust at the base of the tree and later followed by discolored foliage (Hopkins 1909; Furniss and Carolin 1977). Egg galleries are excavated in the inner bark (i.e. phloem or cambium) but the shape of the galleries differ with the species, as some start as straight and linear while others tend to be winding (Wood 1963). Placement of eggs along the perimeter of the egg gallery can be varied and larval feeding may occur individually or in aggregation (Hopkins 1909; Wood 1963; Wood 1982). Damage from extensive larval feeding can cause a loss of vitality and kill trees (Hopkins 1909).

In addition to the mechanical damage incurred to the tree due to an attack, many bark beetles, including the genus *Dendroctonus* carry fungi that can impact trees (Wood 1982; Paine et. al. 1997). Several species of *Leptographium* Lagerb. & Melin, *Ophiostoma* H. & P. Sydow, *Ceratocystis* sensu lato Ell. & Halst and yeasts have been isolated from beetles and or stained sapwood (Robinson 1962; Davidson 1978; Owen et al. 1987; Klepzig et al. 1995; Six and Bentz 2003), all with varying degrees of pathogenicity (Owen et al. 1987). Beetles carry these fungi on their body or in specialized structures known as mycangia. As they enter the tree, they inoculate the phloem with fungal spores. Conifers such as *Pinus* spp. respond to beetle and fungal attack with the production of resin (Reid et al. 1967; Berryman 1972; Smith 1972; Cook and Hain 1986; Christiansen et al 1987; Paine et al. 1988; Popp et al. 1991), toxic chemical compounds (Smith 1963b; Smith 1965; Cook and Hain 1986), and necrotic lesions to isolate insects and fungi (Reid et al. 1967; Raffa and Smalley 1988). But if the tree is weak, unhealthy, or environmental conditions are unfavorable (Lorio et al. 1995) it may be unable to saturate the area around the attack with resin. Without resins or other defensive compounds to isolate fungi and kill beetles, trees can be colonized by fungi. This colonization can lead to the staining of the sapwood by the growth of fungal hyphae, as well as the possibility of death from colonization of tree tissue and toxin releases by the fungi (Coulson 1979; Paine et al. 1997). These fungi may also play a role in attraction of other beetles or as producers of pheromones (Paine et al. 1997) and may also affect the nutritive quality of the phloem and wood of a tree (Whitney 1971; Whitney et al. 1987; Harrington 1993; Paine et al. 1997) for the invading insects.

BIOLOGY OF RED TURPENTINE BEETLE

The red turpentine beetle (RTB), *Dendroctonus valens* LeConte (Coleoptera: Curculionidae, Scolytinae), is a common bark beetle distributed from the northeastern United States and Nova Scotia westward to the Northwest Territories and south into Central America, excluding the southeastern United States (Rykken and Hanson 1999; Erbilgin et al. 2007; Fettig et al. 2008). Although it has been occasionally known to attack and kill healthy trees, RTB is largely known as a secondary pest attracted to resins and volatiles emitted from stumps, stressed, dying or damaged *Pinus* spp., and to a lesser extent *Picea* spp., *Larix* spp. and *Abies* spp. (Hopkins 1909; Smith 1971; Wood 1963;

Wood 1982; Bright 1993; Paine et al. 1997; Rykken and Hanson 1999). Adult RTB are attracted to a number of host volatiles, including α-pinene, β-pinene and 3-carene (Joseph et al. 2001; Sun et al. 2004; Petrice et al. 2005; Erbilgin et al. 2007). These volatiles have been used in trapping and monitoring programs for RTB. Red turpentine beetle populations may increase where regular forest management is common and upon cessation of management, RTB can attack healthy unstressed trees (USDA Forest Service 1985).

Trees are usually colonized by just a few pairs of RTB, which are typically attracted by a number of host volatiles emitted by trees (Hobson et al. 1993; Sun et al. 2004; Erbilgin et al. 2007). Normally, pole sized or larger trees (>25 cm) are attacked a few centimeters above the ground but attacks can extend down into roots and up to two meters above the ground (Hopkins 1909; Wood 1963; Wood 1982). In an attempt to fend off an attack, trees exude resin at attack sites (Figure 1, Figure 2) which may or may not stop the beetles (Beal et al. 1952; Eaton and Lara 1967; Bright 1993; Wood 1982). Successful attacks will present themselves characteristically as small tubes of dried pitch and boring frass (Figure 3, Figure 4). These tubes serve as an entrance and exit, as well as a location to discard boring dust and other byproducts of attack (Hopkins 1909; Smith 1971; Wood 1963; Wood 1982). Larvae develop in the phloem where they congregate and feed in mass and kill large sections of cambium similar to the habits of *Dendroctonus terebrans* and *D. micans* rather than creating individual tunnels or galleries like many other *Dendroctonus* species (Hopkins 1909; Wood 1963; Wood 1982; King and Fielding 1989). Larval feeding activity can kill up to a half of a meter of phloem and cambium at or near the base of the tree (Hopkins 1909; Smith 1971; Bright 1993) and sometimes extending into the roots (Wood 1963; Wood 1982).

The damage associated with RTB may go unnoticed with little economic or ecological impact, or it could present itself as a catface (USAD Forest Service 1985), where the cambium is killed and the outer bark subsequently sloughs off. This damage can often be mistaken for fire damage (Hopkins 1909) or perhaps old logging damage. Areas damaged from larval feeding and then exposed to fire may also present themselves as catfaces (Beal et al. 1952). RTB will also vector the black stain root disease *Leptographium wageneri var. ponderosum* (Harrington et Cobb) and blue stain fungi such as *Leptographium terebrantis* Barris & Perry, *Leptographium procerum* (Kender) Wingfeld and *Ophiostoma ips* (Rumbold) Nannfeldt (Owen et al. 1983; Klepzig et.al.1995). While attacks by RTB sometimes kill host trees, they can predispose trees to attacks by other damaging insects and these stain fungi (Craighead 1950; Eaton and Lara 1967; Furniss and Carolin 1997; Rappaport et al. 2001; Owen et al. 2005). RTB-induced blue stain and catfaces can be cause for concern when they occur at sites being managed for future lumber or pulp production. It is possible that higher paper production costs associated with additional bleaching of blue stained pulp (Byrne et al. 2005) and the downgrading of butt logs and lumber affected by bluestain and catfaces (Ostrander 1971; Ostrander et al. 1971; NELMA 2006) can result in economic losses that may not be severe on a tree by tree basis, but can compound over a forest management area.

SILVICULTURE AND RED TURPENTINE BEETLE

Silvicultural treatments such as pre-commercial thinnings, shelterwood thinnings and clear cuts change site characteristics and can cause damage to trees that are intended to remain as a seed source, nurse trees, future forest or buffers. Under managed conditions, trees with and without residual stand damage become susceptible to RTB (Eaton and Lara 1967). While little is known about how RTB behaves in eastern forests after silvicultural treatments, studies on RTB, western *Pinus* spp. and other *Pinus*-inhabiting bark beetles have shown some management practices can increase residual tree damage or loss (Belanger 1980; Fischer 1980; Bradley and Tuller 2001; Fettig et al. 2006; Komonen and Kouki 2008). Because of their attraction to volatiles produced from fresh resin, stumps, and damaged trees (Smith 1971; Bright 1993), RTB can be found in undamaged trees where cut logs are stored or where silviculture is being practiced (Smith 1971). In managed areas, or areas prone to wind and fire damage, populations can increase and with the cessation of management or disturbance and the lack of easily exploitable stressed trees RTB can shift from stressed trees and stumps to apparently healthy trees (Hopkins 1909).

Additionally, RTB has proven to be an invasive pest in China. Since its introduction in the 1980s and the first reports of damage in the late 1990s, RTB has killed more than 10 million trees on 500,000 ha of forest land (Sun et al. 2004). RTB is highly polyphagous and is common in Chinas' most widely planted pine species, *Pinus tabuliformis* Carriere. It is also likely to reproduce in all pine species in China, giving it the potential to spread nationwide with potentially devastating consequences (Yan et al. 2005; Erbilgin et al. 2007).

I. OBJECTIVES

RTB has been studied for many years with a considerable amount of information originating in the western and Midwestern parts of the United States (Owen et al. 1987; Klepzig et al. 1995; Rappaport et al. 2001; Owen et al. 2005). There has also been an urgency to study RTB in China, where it is a devastating invasive insect. However, there are still knowledge gaps in RTB biology in the eastern United States and how this beetle responds to disturbances caused by silvicultural treatments in *Pinus strobus* L. (eastern white pine). Consequently, it is important to assess the effects of silvicultural treatments on RTB behavior to determine what residual site and tree characteristics create favorable conditions for RTB populations. Additionally, it is important to identify which silvicultural treatments and stand variables contribute to the probability and severity of attack on trees by RTB.

Four silvicultural treatments in white pine stands at the Massabesic Experimental Forest (MEF) in York County, Maine (Figure 5, Figure 6) provided a unique opportunity to investigate RTB behavior in disturbed forests. In the summer and fall of 2008, I assessed how RTB reacts in a shelterwood thinning and the forest adjacent to a group of clearcuts. In the summer and fall of 2009, one low density removal and one high density removal were sampled. One control stand in close proximity to the silvicultural treatments was also sampled in the fall and winter of 2009 and 2010. While these stands were surveyed in 2007 and 2008 using semiochemical baited traps (Dodds et al. 2010), I anticipate little effect on the current study.

Data were analyzed to determine the post treatment site conditions, tree characteristics, damage to residual white pine and the presence of RTB. This information will allow for the determination of what silvicultural treatment and tree conditions affect the probability and severity of RTB attack on residual trees. Based on this data set, management recommendations were developed for the MEF to provide guidance in reducing negative impacts of RTB attacks in treated stands. Specific objectives of this study are:

1. Assess post treatment site conditions and damage to residual *Pinus strobus* in four silvicultural treatments: (1) a shelterwood, (2) a low density pre commercial removal, (3) a high density pre commercial removal and (4) the forest adjacent to a group of clearcuts at the Massabesic Experimental Forest and compare them to an un-managed control site.

2. Assess and estimate the residual tree and site characteristics at the four silvicultural treatments and control site at the Massabesic Experimental Forest to describe the probability of finding RTB in a tree and severity of attacks by RTB to a tree.

3. Create a set of silvicultural recommendations that will help to reduce the probability and severity of attacks by RTB in white pine forests at the Massabesic Experimental Forest.

II. METHODS

STUDY AREA

The study was conducted on the northern unit of the Massabesic Experimental Forest (MEF) (N43.564582°, W-70.641678°) located in York County, Maine (Figure 5). The MEF is comprised of the 683 hectare northern unit and 813 hectare southern unit, which were acquired under the authority of the Weeks Act in the late 1930s and early 1940s for the purpose of research. The MEF is currently managed by the USDA Forest Service, Northern Research Station as an experimental forest that is also open to public recreational use. Historically, the MEF has had a considerable amount of human and natural disturbance ranging from harvesting and farming from the early 1600s through the late 1800s to major fires and storm damage in the late 1940s through the 1950s (Dibble et al. 2004). Although there are numerous wetlands, the predominant land type is rolling hills and relatively flat ground with forest types consisting primarily of white pine *Quercus rubra* L. (red oak)/ *Acer rubrum* L. (red maple) and areas of *Tsuga canadensis* L. (Carriere) (eastern hemlock). Because of the numerous and extensive disturbances management has been sporadic. Currently, much of the regenerated forest is overstocked and of poor quality.

SITE SELECTION

Within the northern unit of the MEF, four white pine dominated sites were harvested (Figure 6), two in the fall and winter of 2007-2008 and two in the fall and winter of 2008-2009. Each of the four harvested study sites was managed using a unique silvicultural treatment. Management was initiated on a 4.5 hectare shelterwood cut (Figure 7, Figure 8) and a 4.9 hectare clear cut (Figure 9, Figure 10) in the fall and winter of 2007 and 2008. Sampling was conducted in the shelterwood and around the clearcuts in the summer and fall of 2008. Management was also initiated on two pre-commercial thinnings in the fall of 2008. A 17 hectare high density removal (Figure 11, Figure 12) and 16 hectare low density removal (Figure 13, Figure 14) were then completed in the winter of 2008 and 2009. Sampling in the high and low density removals was conducted in the summer and fall of 2009. Within the high and low density removals, a 5 +/- hectare block was selected and sampled for this study. Control plots (Figure 15, Figure 16) were sampled in the fall of 2009 and the winter of 2010 and were located within the unmanaged forest adjacent to the silvicultural treatments. The forest where the control plots are located is a representative sample of the unmanaged and overstocked white pine dominant forest that the managed treatments consisted of prior to harvest.

The area containing the study was fairly uniform across the five study sites. The soils consisted of an Adams-Colton Association, with 0-8% slope (Adams loamy sand, Colton gravelly loamy coarse sand, Croghan loamy sand and Naumburg sand), all of which are well drained coarse textured sandy and gravelly outwash. The Adams-Colton Association is also moderately to severely acidic. All treatments are suited towards white pine, but in a measure of productivity, the shelterwood and clearcuts have a slightly higher site index for white pine (62-65) then the remaining sites (60) (Flewelling et. al. 1982). Much of the study area was cleared prior to the 1947 fires and consisted of brushy abandoned farmland with occasional white pine saplings. As a result, the intense fires of

1947 burned almost the entire area and initiated the conversion of the area to white and red pine plantation in the 1950s (Dibble et. al. 2004). The area composed of the shelterwood escaped burning in the fires of 1947 and as a result, is older than the remaining sites. As with a majority of the northern unit of the MEF, the overstory at all sites was predominantly white pine with a mix red maple and red oak. Understory species consisted of a mix of red maple, American beech as well as eastern hemlock and *Abies balsamae* L. (Mill) (balsam fir).

Though it is not unreasonable to believe that the results of this study can be applied to southern Maine and southeastern NH, it must be mentioned that this study was not replicated and should be considered a case study of the silvicultural activities being conducted at the MEF. Being a case study, the results should be considered relevant to the MEF while also illustrating that the issue should be explored further in a replicated study in other areas when feasible.

SAMPLING METHODS

All three treatments, the forest adjacent to the clearcuts and the control were sampled with a system of 20 fixed radius plots, each with a 10 meter radius and spaced 40 meters apart to allow 20 meters between plot edges. Plots within the high density removal, the low density removal and shelterwood were established on transects, forming a grid that was buffered 15 meters from stand edges and woods roads. Plots at the control treatment were established in a similar manner as the treated areas and at least 40 meters from any silvicultural treatment. Plots established at the clearcuts were placed around the perimeter of the clearcuts in the forest adjacent to the harvested area. Plots centers were located 10 meters from the edge within the forested areas surrounding the clearcuts with a spacing of 40 meters between plots (Figure 17). In all treatments the goal was to sample approximately 10-15% of the total treatment area. Sample data were taken at each plot to assess post treatment site conditions and the residual logging damage.

All tree data was grouped in three categories, tree measurements, vicinity measurements and plot level measurements. Tree measurements were those that consisted of measurements conducted to the sample trees, while vicinity measurements are those that were taken in the area adjacent to the sample trees. Plot level measurements were those common to all trees on the plot and expanded to a per hectare measurement. These groupings are detailed in Table 1. Diameter at breast height (DBH) in centimeters was collected for white pine and non host species. DBH was recorded for all live trees that were greater than or equal to10 cm. DBH was used to accurately calculate the individual tree basal area, residual basal area of all live white pine and hardwood and other non host species on each plot expanded to per hectare (hereafter referred to as residual pine basal area and residual hardwood basal area respectively) as well as total basal area on each of the plots. All basal area calculations were recorded in square meters per hectare. Crown classes (overtopped, intermediate, co-dominant and dominant), total tree height in meters, length of live crown in meters, live crown ratio as a percent of the total tree height and crown exposure were collected to assess the characteristics of residual white pine post harvest. The numbers of attempted RTB attacks were recorded for each tree on a plot. Attempted attacks were recorded in the lower bole (below 3 meters) as RTB rarely attacks at greater heights. Attempted attacks were also recorded for all visible sections of the roots. All attempted RTB attacks, in the form of pitch tubes and streaking pitch will hereafter be referred to as RTB attacks. Damage to the lower bole below 3 meters related to harvesting activities such as scrape, missing bark and resinosis, as well as lower bole damage incurred by other means was recorded for each tree. A total basal area of all cut pine stumps and pine snags less than or equal to a year old within 12 meters of each sample tree (hereafter referred to as basal area of stumps) was recorded. It is generally accepted that host volatiles are not effective at long distances and as a result the distance of 12 meters was chosen. A series of presence or absence (yes or no) measurements were also recorded for variables that would have been too subjective for assigned values. Presence or absence observations consisted of soil compaction or disturbance that exposed mineral soil within 5 meters of the tree, presence or absence of other insects or fungi in the lower bole below 3 meters, presence or absence of exposed or damaged visible roots and presence or absence of dual leaders (Table 1).

STATISTICAL ANALYSIS

Data were collected at the three silvicultural treatments, the forest adjacent to a group of clearcuts and a control site in the summer and fall of the year following the silvicultural treatment. The control treatment was sampled in the fall and winter of 2009 and 2010 as there was no anthropogenic disturbance to initiate RTB activity. A total of 100 plots were sampled within the four treatments and the control, with 829 total trees consisting of the experimental units. JMP 8.0.2 (SAS Institute Inc.) was used to calculate percentages, means (+/- standard error) for overall site characteristics and characteristics of white pine. Additionally, JMP 8.0.2 was used to test for significant differences in variables using the ANOVA and Tukey's HSD test function was used to separate means.

Additionally, two generalized linear models (GLM) were chosen to assess the data. The initial set of data collected in the field consisted of 20 variables that were chosen based on knowledge of the system and treatment methods. Of those initial variables, 13 were compared with a correlation matrix. Using correlation analysis (PROC CORR, Pearson Correlation Coefficients SAS 9.2, SAS Institute Inc), all variables were cross correlated and those coefficients with values greater than 0.5 were assessed for inclusion or rejection in further models (Table 2). Site and nine other variables (DBH, residual white pine basal area, residual hardwood basal area, height, crown class, live crown ratio, logging damage to the lower bole, basal area of stumps and exposed or damaged roots) were chosen for analysis based on their perceived importance and reliability of collection in the field. The nine variables were used in the two GLM's. These models were used to assess the probability of predicting RTB attack and the probability of severity of an RTB attack in white pine.

The first model looked at all white pine trees as the experimental unit. A binary logistic regression model (PROC LOGISTIC, SAS 9.2, SAS Institute Inc) was used for every white pine on the plots to predict the probability of a tree being attacked by RTB (i.e. RTB found or not found). The use of a logistic regression model was appropriate in this case because the dependant variable (RTB attack) had only two outcomes (attacked/un-attacked); the data consisted of qualitative variables (i.e. site, crown class, crown exposure, presence or absence of exposed mineral soil, presence or absence of other insect or disease, presence or absence of split leader) and quantitative fixed effects variables (i.e. all basal area measurements, dbh, height, live crown ratio, logging damage) and a non-normal response variable.

The second model looked at attacked white pine trees only as the experimental unit. A generalized linear model using pseudo-likelihood (PROC GLIMMIX, SAS 9.2, SAS Institute Inc) was used for only the trees where an attack was recorded to predict the probability of severity of attack by RTB. The model was a lognormal distribution model with an identity link function. A variety of models and link functions were tested for fit. The lognormal distribution model with the identity link function was used because it had the lowest Akaike Information criteria values. Although the lognormal distribution model is typically used with continuous data, it was still used with the count data from this study to address the right skewed data. As with the logistic regression, the nine final variables were evaluated to establish significance in regards to severity of RTB attacks on host trees.

III. RESULTS

SITE CHARACTERISTICS

A total of 829 white pine trees were sampled from the four treatments and the control, with 17.2% having attempted attack sites attributed to RTB. The high density removal had the greatest percentage of attacks with 48.9% (Figure 18). Ten treatment level variables were tested for differences in residual stand characteristics. Significant differences among treatments were observed for DBH ($F_{4, 824}$= 95.06; P< 0.0001), Height ($F_{4, 824}$= 170.01; P< 0.0001) and LCR ($F_{4, 824}$= 95.78; P< 0.0001), with the shelterwood having the largest means for each variable (Table 3).

The mean percent logging damage for white pine trees in the low density removal, high density removal and shelterwood were not significantly different from each other, but were significantly different than the forest adjacent to the clearcuts and control treatment which had no damage ($F_{4, 824}$= 18.38; P< 0.0001) (Table 4). The low density removal and the shelterwood were the only treatments with any exposed or damaged roots (Figure 19). Significant differences were found among treatments in terms of basal area of stumps ($F_{4, 824}$= 383.61; P< 0.0001) (Table 4) with the control and forest adjacent to the clearcuts equal, while the low density removal and the shelterwood were similar but lower than the high density thinning (Table 4). There were significant differences among treatments in the amount of residual forest trees left in each treatment or adjacent to it as in the case of the clearcuts ($F_{4, 95}$= 13.69; P< 0.0001). The white pine basal area at the control site was significantly larger than the white pine basal area of the forest adjacent to the clearcuts, and the residual white pine at the shelterwood, the low density removal and the high density removal (Table 5). The hardwood basal area showed no significant differences between the forest adjacent to the clearcuts and the control site, but they were significantly different than the residual hardwood basal area at the other three treatments ($F_{4, 95}$= 22.73; P< 0.0001) (Table 5). The co-dominant crown class was the most common crown class in all sites and treatments with the low density removal being 100%, the high density removal and the shelterwood nearly 100% co-dominant and the clearcuts near split between co-dominant, intermediate and overtopped (Figure 20).

PRESENCE OR ABSENCE OF RED TURPENTINE BEETLE

To predict the probability of attack by RTB, all white pine trees were assessed. The nine final variables were run through the binary logistic regression model to determine if there were any significant relationships among them and the probability of finding RTB in residual and forest trees after management. Five of the nine variables; site (χ^2 = 0.002), residual white pine basal area (χ^2=0.0022), residual hardwood basal area (χ^2 = 0.0345), height (χ^2=0.0339) and logging damage to the lower bole (χ^2=0.002) were shown to be significant in assessing the probability of finding RTB. The results are listed in the Type III Analysis of Effects Table detailing the hypothesis tests for each variable contained in the model (Table 6).

Using the Odds Ratio Estimates (Table 7) that were generated as part of the binary logistic regression model, it was found that the probability of finding RTB colonizing a tree is nearly equal in the shelterwood, the high density removal and the low density removal. The Odds Ratio Estimates indicates that the odds of finding infested trees at the shelterwood, the high density removal and the low density removal are more likely that you would find infested trees in the forest adjacent to the clearcuts the control treatment. The Odds Ratio Estimates also illustrate that for factors shown to be significant for presence or absence, increases or decreases in values have an effect on the probability of attack by RTB in a tree. As residual white pine and hardwood basal areas increase (i.e. higher stocking levels), the probability of attack decreases, while increases in height and logging damage increase the probability of attack by RTB (Table 7). It should be stated that the probabilities and percentages in the Odds Ratio Estimates Table should be looked at in their relationship to each other, rather than for the actual values. It is difficult to justify the use of the actual probabilities and percentages with an un-replicated and narrow dataset.

SEVERITY OF RED TURPENTINE BEETLE ATTACKS

Looking at attacked trees only as the experimental unit, all nine variables were tested in the lognormal model to determine if any were significant predictors of the severity of RTB attacks on residual and forest trees after management activities occurred. Of the nine variables tested, basal area of stumps (Pr>F= <0.0071) was the only variable to show any significant relationship in regards to severity of attack. The results are listed in the Type III Test of Fixed Effects Table detailing the hypothesis tests for significance of each fixed effect contained in the model (Table 8).

IV. DISCUSSION

The silvicultural treatments sampled in this study consisted of a shelterwood cut, a set of clearcuts and two levels of pre-commercial thinnings. These treatments were designed to improve tree quality and enhance the wildlife habitat of a forest that contained overstocked and poor quality stands. While enhancing economic and ecological benefits is the goal of management, silvicultural treatments often have unintended results such as disruptions in hydrologic processes (Ensign and Mallin 2001), soil disturbance and compaction (Wert and Thomas 1981; Eliasson 2005) and damage from equipment and felling to residual forest trees and seedlings (Fairweather 1991; Youngblood 2000; Heitzman and Grell 2002). Silvicultural treatments can also affect insects in a variety of ways. Work from the western United States has shown that *Dendroctonus ponderosae* Hopkins favors larger poor quality *Pinus contorta* Douglas and as such, damage is often reduced after harvest as a result of changes in tree vigor, reductions in average stand diameter and the microclimate within the forest stand (Amman et.al. 1988). *Dendroctonus frontalis* Zimmermann is another species of bark beetle whose damage is reduced by thinning to develop mixed species conditions (Schowalter and Turchin 1993) and more vigorous forest stands (Hedden 1978). Although these are not eastern species and more aggressive bark beetles than RTB, some similarities to the east can be drawn. Silvicultural activities can have other impacts on residual trees that influence bark beetles including fire damage from prescribed burning operations, soil and root compaction, as well as residual logging damage in the form of broken branches and scraped bark from heavy machinery during harvest. These types of stand damages have been shown to increase the activity of a number of species of bark beetles in the south and west (Belanger 1980; Fischer 1980; Bradley and Tuller 2001; Fettig et al. 2006; Komonen and Kouki 2008). Some of the unintended consequences of forest management at the MEF came in the form of RTB activity and damage to the residual trees. Resulting stand conditions and tree characteristics such as residual white pine and hardwood basal area, basal area of stumps, logging damage and others can work alone or in concert to act to attract insects such as RTB. RTB is an insect that is attracted to fresh cut stumps as well as damaged and stressed pole sized trees (Hopkins 1909; Wood 1963; Smith 1971; Wood 1982), but it can infest trees in close proximity to cut stumps (Bolt and Van Deusen 1974). As a result, RTB can benefit from conditions present during and after forest management.

It is evident from the literature that forest entomologists agree that RTB is of little economic or ecological importance on its own in North America, and in its native range RTB rarely kills large numbers of trees (Hopkins 1909; Wood 1963; Wood 1982). But, while attacks may not kill a tree, other impacts may occur. RTB attacks the lower bole of *Pinus* spp. and reproduces within the cambium/phloem layers. Economically, the lower bole of any crop tree contains 70% of the value and in white pine, the outer wood or sapwood of the lower bole is where the highest quality and most valuable lumber is located (D. Quigley, Personal Communication, August 8, 2010). These two important factors are considered when grading logs and lumber. Damage from RTB can show up in butt logs as a catface, similar to those observed and caused by *Dendroctonus ponderosae* in *Pinus contorta* (Mitchell 1983; Stuart et al. 1983). RTB damage may also show up as blue stain (Bolt and Van Deusen 1974) from beetle introduced fungi such as *Leptographium terebrantis*, *Leptographium procerum* and *Ophiostoma ips* (Owen et al. 1983; Klepzig et.al.1995), which is considered a scaling defect that can reduce merchantable volume (Ostrander 1971; Ostrander et al. 1971) by downgrading or by removal of portions of the butt log. Over time, damage can also be over grown and become an inclusion in the sapwood. Coupled with the difficulties of marketing excessively stained lumber (Byrne et al. 2005), included bark from closed over catfaces, pitch pockets and other defect associated with feeding can downgrade the most valuable lumber sawn from the sapwood of the butt log (NELMA 2006). Though these economic effects are small when looking at individual logs, if RTB is common in a stand that is being managed for sawtimber the combined economic effects may be substantial. Additionally, forest stands that are managed for pulp used in the papermaking process can also be negatively impacted by blue stained material. Blue stain does not adversely affect the structure of wood used in papermaking, but there are typically additional costs associated with more intensive brightening procedures (Byrne et al. 2005). Consequently, the monetary value of residual crop trees can decline making profit more difficult. Because of post harvest RTB activity at the MEF, this case study was undertaken to identify tree and stand level conditions following silvicultural treatments that influence RTB in managed white pine stands in southwestern Maine.

PRESENCE OR ABSENCE OF RED TURPENTINE BEETLE

Analysis showed that there was a significant difference in the sites as they relate to the probability of having RTB present in trees. The Odds Ratio Estimates indicated that it was more likely to find RTB in the shelterwood, the high density removal and the low density removal treatments than the forest surrounding the clearcuts or the control stand. Just looking at the relationship rather than the actual percentages outlined in the Odds Ratio Estimates Table, it appears that other than unmanaged forest, the clearcuts are least likely to have RTB activity following harvest at the MEF.

It is understandable that the probability of finding RTB in the forest adjacent to the clearcuts would be lower due to the fact that it has favorable values for the factors that were found to be most important (high residual white pine basal area, high residual hardwood basal area, almost no logging damage and lower heights) through regression analysis. With the exception of edge trees, the forest adjacent to the clearcuts is quite similar to the forest at the control treatment which is much less likely to have RTB present than any other treatment. Compared to other treatments, the trees adjacent to the clearcuts had almost no logging damage, the lowest mean height and are significantly different from the shelterwood with higher mean residual white pine and hardwood basal area. The high density removal, the low density removal and shelterwood all have a mean logging damage of roughly 1%, which was also shown to raise the probability of finding RTB. Though these factors were found to be significant when assessing the probability of finding RTB attacks in a treatment, there are also other factors such as stem density of white pine and non host species as well as the ratio of trees of suitable size for colonization that were not accounted for in the analysis. There may also be other factors not evident in the field that could contribute to the absence of RTB attacks in the forest adjacent to the clearcuts or the controls. With RTB being attracted to stressed trees, some presence in the control stand would be expected. However, the few attacks that were recorded in the control stand were on trees that had previous damage from wind and perhaps lightning. Beyond those few attacks, no others were recorded. It appears to be a similar situation in the forest adjacent to the clearcuts. The few attacks that were at the clearcuts were recorded along the edge, closest to the management, while there were none in the overstocked but undamaged forest beyond the forest edge. Microclimate could also play a role in RTB behavior. In open or thinned stands, the soil and tree surfaces tend to increase in temperature due to solar heating. Increased temperature at the clearcuts could help to reduce the presence of RTB in the adjacent forest through the disruption of volatile plumes by way of convection (Schroder and Buck 1970; Rosenberg et al. 1983; Amman 1988). Conditions in clearcuts such as open space, ample sunlight and airflow may also cause stumps and damage drying out quickly. There is a short window of attraction for insects such as RTB that cue in on host volatiles. Stumps and damage exposed to open conditions of a clearcut can be ineffective in a short amount of time as volatiles are emitted and quickly dissipate as the stumps and damage dry out. However, if stumps and damage are effective at attracting RTB in the area of the clearcuts, RTB may attempt to use the stumps as host material or move through the stand due to the lack of host trees in close proximity. Conversely, volatile dispersal by way of convection may also be possible in the other treatments (excluding the control) with the openness of the stands but may be less so due to a crown layer being present. Additionally, the damage and stumps in the treatments other than the forest adjacent to the clearcuts have a small amount of shading and protection from the crown layer. This added protection may extend the period of volatile release in close proximity to attractive host trees.

The analysis also showed that residual white pine and hardwood basal area are important factors in respect to the presence or absence of RTB. In general, as you increase both residual pine and hardwood basal area, you decrease the probability of finding RTB attacks on the trees. The average residual white pine basal area adjacent to the clearcuts was relatively high, although not statistically different than the shelterwood at 16.0 $m^2 \pm 1.3$ (Table 5). With an increased residual white pine basal area contributing to a decrease in the probability of finding RTB it is understandable that the forest adjacent to the clearcuts would have less RTB present. It should be noted that the remaining treatments have lower residual white pine basal area per hectare, but only the control and the high density removal are statistically different (Table 5).

The role of the large component of non-host species as a possible deterrent to RTB attack should be considered. Belanger (1980) and others (Schowalter and Turchin 1993; Belanger et al. 1993) have suggested that thinning to develop mixed species stands can reduce damage from *Dendroctonus frontalis* and although it is a more aggressive beetle, it illustrates the point that non host species in a stand can make it more difficult for an insect to locate a host. However, results for residual white pine are in contrast with the findings from others that have found a positive relationship between higher host basal areas and increased probability of attack (Negron et al. 2008). Although they are more aggressive species than RTB, there is great deal of evidence suggesting that higher basal area per hectare results in higher probability of attack for beetles such as *D. ponderosae* and *D. frontalis*, and thinning increases tree vigor and reduces attack (Hedden 1978; Belanger 1980; Matson et al. 1987; Schmitz et al. 1989; Belanger et al. 1993), albeit in the subsequent years following harvest.

These examples mainly pertain to pure or near pure forest stands in the south and west, unlike the mixed forest conditions at the MEF which may actually benefit from a greater basal area per hectare with a mixed species composition. With increased residual pine basal area two factors should be considered, number of trees and size of trees. To illustrate this point I will compare the treatments with some of the highest and lowest percentages of attack; the shelterwood and the forest adjacent the clearcuts (Figure 18): (1) A large number of pole and smaller sized trees (< 25 cm) can result in a large residual basal area. However, this forest may also provide a smaller host resource consisting of a limited number of adequately sized trees, thus reducing the probability of attack by RTB. If you add a large non host component (size not critical) to this scenario, there is additional interruption of RTB with crowding of host and non host species in the stand. This situation makes it difficult for RTB to locate adequate host trees and the probability of attack can be reduced to a greater extent. This case may be illustrated by the data for the clearcuts. Although stems per hectare are not reported, the residual pine and hardwood basal areas are very high and diameter of pine significantly smaller than the shelterwood treatment. This hints to an overcrowded stand of various sized host and non host trees (Table 3, Table 5). (2) A smaller number of very large diameter trees (>25 cm) also results in a large residual pine basal area and provides a substantial and conspicuous resource for RTB, as there is very little residual hardwood basal area present to interrupt host location. This case is well illustrated by the shelterwood treatment. The results from this study show there is no significant difference in residual basal area of pine between the shelterwood treatment and the forest adjacent to the clearcuts (Table 3). This result may suggest that the probability of RTB attack may be better interpreted by the stand density and size of trees rather than residual pine basal area. (Table 3, Table 5). Although not analyzed in this case study, the relationship between stand density and tree size in relation to host suitability, location by RTB and probability of attack should be further investigated in place of or in conjunction with residual pine and hardwood basal area.

An interesting theory put forth suggests that forests may proceed through phases of susceptibility. Anhold and Jenkins (1987) suggest that trees long since crowded and stressed for a number of years have a low resin potential as well as reduced phloem thus making them less attractive as a host. As with much of the RTB work, this study was based on western insects and *Pinus* spp. and is difficult to translate to the east but could warrant additional consideration.

The percentage of logging damage to the lower bole of sample trees is another variable that plays a large role in the probability of finding an RTB infested tree as it relies generally on host monoterpenes and less on aggregation pheromones (Borden 1982; Hobson et. al. 1993; Sun et al. 2004; Erbilgin et al. 2007). With an increase in bole area damaged you can expect an increase in the probability of finding RTB in a tree (Table 7). Several studies have suggested that RTB is attracted to host volatiles (Joseph et al. 2001; Sun et al. 2004; Petrice et al. 2005; Erbilgin et al. 2007). It is also documented that RTB attacks stressed and damaged trees (Hopkins 1909; Wood 1963; Smith 1971; Wood 1982), as well as being commonly attracted to tree damage and stumps associated with logging (Smith 1971; Boldt and Van Deusen 1974). Given this information, the finding associated with the relationship of logging damage and RTB attacks is not surprising. The mean percentage of logging damage was zero in the control (no management) and near zero in the forest adjacent to the clearcuts (management in the clearing, not the edge forest), and the percentage of attacks for both was also relatively low (Figure 18). Although the shelterwood did have a measurable amount of logging damage is was not significantly different than any treatment, except the control (Table 4). These mean percents of logging damage coupled with a higher percent of attacks in Figure 18 show that logging damage to the lower bole, however small may play a role in probability of attack by RTB.

There are some factors to consider when drawing conclusions about the results for logging damage and RTB attacks. The high and low density removals and the shelterwood all had logging damage, while attacks observed at the control site were on a small number of trees that had no logging damage, but suffered bole and large limb breakage possibly due to wind damage. The forest adjacent to the clearcuts had almost no logging damage, with a very small number of edge trees attacked due to reasons mostly other than logging damage. It should be understood that the trees at all other treatments were smaller in size than the larger trees at the shelterwood (Table 3). These additional factors could pose a problem when assessing the importance of logging damage.

It is likely that the significance of height in this study could be overstated due to pseudo-replication and site characteristics of the shelterwood treatment. Although all the treatments have similar soils, species composition and site indices that favor white pine, there are some distinct differences in the shelterwood with respect to age and the values for DBH (44.8 cm $\pm$ 1.1) and height (25.0 m $\pm$ 0.04) (Table 3). During the fires that spread throughout southeastern Maine in 1947 large parts of the MEF burned. This is true of the area sampled for this case study with the exception of the shelterwood (J. Janelle, Personal Communication, December 7, 2010). During the 1950s all areas that previously burned were developed as plantation while the shelterwood treatment, untouched by fire was left growing as natural forestland. As a result, the area consisting of the shelterwood treatment grew with a more natural spacing with fewer larger white pines, while the remaining treatments are typical unmanaged plantation with smaller and younger trees that have become overcrowded.

SEVERITY OF RED TURPENTINE BEETLE ATTACKS

The severity model demonstrated that of all characteristics and conditions estimated, basal area of stumps and year old snags within 12 meters of a sample tree was the only factor that was statistically significant. Because there were so few snags at the time of sampling, this discussion will mainly focus on the role of stumps within 12 meters of sample trees.

Although the stumps at the MEF treatments were cut low as a contract requirement, the relationship between RTB severity and stumps is not surprising when you consider that RTB is attracted to host volatiles (Borden 1982; Hobson et. al 1993; Sun et al. 2004; Erbilgin et al. 2007), as well as stumps and stressed or damaged trees (Hopkins 1909; Woods 1963; Smith 1971; Woods 1982; Bright 1993). In other areas of New England and the MEF, stumps of cut white pine were debarked and shown to have attracted RTB as well as provided successful resources for brood development (Personal observation 2009). Additionally, it has been shown that hundreds of saproxylic beetles, including bark beetles use high stumps (Lindhe and Lindelöw 2004; Abrahamsson and Lindbladh 2006) as well as low stumps (Hjältén et al. 2010) for breeding and reproduction.

The forest adjacent to the clearcuts had lowest percentage of attacks (8.3%) and the lowest basal area of stumps within proximity of sample trees (0.2 $m^2 \pm 0.1$) (Figure 18 and Table 4), while at the same time, the attack percentages for the high density removal had the highest attack percentage (48.9%), and the highest basal area of stumps (0.9 $m^2 \pm 0.1$). A contract requirement for all the treatments was to cut all stumps close to ground level and removing all slash and debris, effectively removing almost all above ground cut material. Perhaps another reason that RTB attacks were more severe at treatments with higher basal area of stumps is because those stumps that were present were emitting volatiles but offered too little resources for RTB (Hopkins 1909). It is possible that with volatile emitting stumps present and no real resources or debris available for colonization, RTB severity increased by the insect moving into trees. Microclimate may have also played a role in the effects of the basal area of stumps. Stumps at the clearcuts may have been affected by the convection and drying process mentioned previously, (Schroder and Buck 1970; Rosenberg et al. 1983; Amman 1988) which could reduce severity of RTB attacks. Stumps in the other treatments that were in close proximity to trees may have been effective emitters of host volatiles for a longer period of time due to the protection of the forest stands and shade of the crown layer. As a possible result, the remaining treatments had a higher percentage of RTB attacks per tree.

It is important to consider that the basal area measurement for stumps is a total. The basal area of all stumps within 12 meters was summed to obtain one value and as a result, it may be difficult to determine the usefulness of the stumps as a resource. Large basal area values could represent a few large stumps that could provide an excellent source of host volatiles and habitat for brood, or a number of smaller stumps that could easily dry out providing reduced habitat and a low host volatile release. Upon completion of analysis the issues regarding the density of stumps around a tree and suitability of those stumps as a resource became evident. This is similar to the stand density and residual basal area question discussed previously. RTB is known to favor pole sized and larger trees (>25 cm), so the diameter and number of stumps may be as critical as the total basal area of stumps within 12 meters of a tree when assessing the importance of this resource to the severity of RTB attack.

V. CONCLUSIONS

It is difficult when studying effects of silviculture on residual stand conditions to obtain enough sites to replicate a study to the point where results are relevant to a broader geographical region. It was not possible to replicate this case study at the MEF where only five treatments were available for analysis. Of the five treatments, the trees at the shelterwood were older and larger than any other treatment, while the forest adjacent to the clearcuts was similar to the controls in that they were both essentially unmanaged forest. Additionally, the high and low density removals differed only slightly from each other.

Although the five sites differed, they also had some characteristics such as common history, soils and species composition that allowed for some strong comparisons and relevant results for the MEF. Ultimately, the significance of the variables chosen for this case study are relevant to the treatments analyzed, and the results should be approached with caution and with the understanding that they pertain directly to the MEF treatments. The results of this case study can also be used as a basis and justification for continued research into the factors that play a role in the probability and severity of RTB attacks. With that caveat, there are some assumptions that can be made about RTB at the MEF and some possible methods to reduce its activity.

RECOMMENDATIONS

Some of the factors that are significant to the possibility and severity of attack by RTB may be difficult to focus on as a definitive tool to alleviate a potential problem. It may be important to look at all these factors together and devise an acceptable combination that will bring the probability and severity of RTB attacks to an acceptable level. As mentioned previously, RTB is not considered a particularly devastating pest, but it does attack many trees in managed sites. Being proactive in using silviculture to enhance the quality of a stand should not stop at the tree being removed, but should also protect the residual forest. However, it may not be appropriate to manage RTB on every white pine site at the MEF. If there are stands that are high quality and of exceptional value then RTB management may be in order. If high quality logs and lumber are the goal, then keeping RTB out of the lower bole of crop trees could add value to forest products in an industry that has such a narrow profit margin. Some management techniques that could be employed or practiced to reduce the presence and severity of RTB and protect profit in high quality stands are as follows.

1. Manage with group cuts or clearcuts to achieve less residual logging damage to the trees present. Group cuts and clearcuts can also serve to keep fresh cut stumps away from the residual forest as they will be centrally located within openings. These stumps will likely dry out quickly and be ineffective as a volatile source. Group cuts and clearcuts also allow for the convection and disruption of host volatiles from a site.

2. If group cuts and clearcuts are not an option, retain some hardwood in the stand. In a mixed species forest a non host component can interrupt RTB host selection, while providing fewer host species available for colonization by RTB. Additionally, many of the host species present may not be a viable resource as a result of undesirable tree characteristics.

3. Regardless of the method of silviculture practiced, avoid lower bole damage. By using good logging practices you can reduce tree damage thereby reducing the probability of RTB attack. If trees are damaged, remove them as part of the silvicultural treatment.

4. When thinning high value stands, it may be appropriate to use synthetically produced volatiles in a "push pull" manner (Cook et al. 2007). Although there is little evidence that non host volatiles will protect trees from attack, RTB has been shown to respond to non host volatiles in trapping experiments (Fettig et al. 2008). There has also been some experimental success in the west with non host volatiles and bark beetle deterrence (Borden et al. 1998) and push pull trapping. By deploying non host volatiles within strands, insects may be "pushed" out of the stand and "pulled" to traps baited with host volatiles. Although this method is untested in the east, it may merit exploration as a management option.

Red turpentine beetle damage may not be an ecological or economic catastrophe. Although RTB activity is thought to provide the impetus of decline of forest health and facilitate attack by other insects, this is not readily apparent at the MEF study sites, but it may be in the future. More importantly, one should consider the possible effects RTB has on the economic value of white pine sawlogs and pulp logs. Because of the possibility of value loss in sawlogs and lumber due to bluestain and defect, and value losses in pulp production attributed to additional brightening costs, this issue should be explored further. In an industry as unstable as the forest products industry, every opportunity to protect profits and residual forest trees should be pursued. Although it is unlikely that RTB can be eliminated from silvicultural treatments, it may be possible by addressing the factors that favor its activity to keep it at levels that will have minimal impact.

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TABLES

Table 1. Initial variable list prior to vetting and correlation procedure.

Variable	Variable Group	Units	Variable Description
DBH[a]	tree	cm	Diameter in $\geq$ 10cm
Basal Area	plot	m^2	Individual tree basal area
Plot Basal Area	plot	m^2	Basal area of all trees on the plot
Plot Pine Basal Area[a]	plot	m^2	Basal area of all uncut *P. strobus* on plot expanded to per hectare
Hardwood Basal Area[a]	plot	m^2	Basal area of all hardwood on plot expanded to per hectare
Crown Class[a]	tree	1-4	Dominant, Co-dominant, Intermediate, Overtopped
Crown Exposure	tree	1-5	Sides of the crown exposed to light, including top
Height[a]	tree	m	Total height of tree
Crown Length	tree	m	Height of live crown
Live Crown Ratio[a]	tree	%	% of tree that is live crown
Stumps within 12m	vicinity	count	Number of fresh cut stumps within 12m of tree
Basal Area of Stumps and Snags[a]	vicinity	m^2	Basal area of stumps and year old snags within 12m of tree
Logging Damage[a]	tree	10% class	Lower bole damage ($\leq$ 3m) by management
Other Damage	tree	10% class	Lower bole damage ($\leq$ 3m) by other means
Exposed or Damaged Roots[a]	tree	Y,N	Presence exposed or damaged roots
Other Insects	tree	Y,N	Presence of other insects in lower bole ($\leq$ 3m)
Fungi	tree	Y,N	Presence of fungi in lower bole ($\leq$ 3m)
Soil Compaction	vicinity	Y,N	Compaction or exposed mineral soil within 5m of tree
Split Leaders $\leq$ 3m	tree	Y,N	Presence of other insects in upper bole ($\leq$ 3m)
D. valens Attacks[b]	tree	count	Number of attempted attack sites $\leq$ 3m

a. Variables retained following vetting and correlation procedure
b. Response variable

Table 2. Correlation matrix with final variable selections.

Pearson Correlation Coefficients, N = 829
Prob > |r| under H_0: Rho=0

	dbh	treeba	plotba	pineba	hwba	crown class	crown exposure	height	live crown	logging damage	stumps ba	soil compact	exp/dam roots
dbh dbh	1	0.96092 <.0001	-0.19493 <.0001	-0.07878 0.0233	-0.23972 <.0001	-0.50538 <.0001	0.50455 <.0001	0.54374 <.0001	0.52445 <.0001	0.10261 0.0031	0.35676 <.0001	0.35629 <.0001	0.23034 <.0001
treeba	0.96092 <.0001	1	-0.12255 0.0004	-0.04013 0.2484	-0.16691 <.0001	-0.37214 <.0001	0.3749 <.0001	0.50222 <.0001	0.51664 <.0001	0.07259 0.0367	0.29173 <.0001	0.28181 <.0001	0.20402 <.0001
plotba	-0.19493 <.0001	-0.12255 0.0004	1	0.85569 <.0001	0.4509 <.0001	0.04194 0.2277	-0.42302 <.0001	0.23176 <.0001	-0.28216 <.0001	-0.21901 <.0001	-0.66412 <.0001	-0.71983 <.0001	-0.17445 <.0001
pineba	-0.07878 0.0233	-0.04013 0.2484	0.85569 <.0001	1	-0.07607 0.0285	-0.07582 0.029	-0.23932 <.0001	0.35682 <.0001	-0.27323 <.0001	-0.1509 <.0001	-0.44666 <.0001	-0.50605 <.0001	-0.09683 0.0053
hwba	-0.23972 <.0001	-0.16691 <.0001	0.4509 <.0001	-0.07607 0.0285	1	0.2116 <.0001	-0.40229 <.0001	-0.16889 <.0001	-0.0724 0.0371	-0.1617 <.0001	-0.50923 <.0001	-0.51413 <.0001	-0.16912 <.0001
crown class	-0.50538 <.0001	-0.37214 <.0001	0.04194 0.2277	-0.07582 0.029	0.2116 <.0001	1	-0.73572 <.0001	-0.52089 <.0001	-0.1572 <.0001	-0.06677 0.0546	-0.1734 <.0001	-0.18912 <.0001	-0.06427 0.0644
crown exposure	0.50455 <.0001	0.3749 <.0001	-0.42302 <.0001	-0.23932 <.0001	-0.40229 <.0001	-0.73572 <.0001	1	0.35415 <.0001	0.16805 <.0001	0.19011 <.0001	0.45492 <.0001	0.51433 <.0001	0.13852 <.0001
height	0.54374 <.0001	0.50222 <.0001	0.23176 <.0001	0.35682 <.0001	-0.16889 <.0001	-0.52089 <.0001	0.35415 <.0001	1	0.12331 0.0004	-0.00556 0.8731	0.07235 0.0373	0.03339 0.337	0.11409 0.001
live crown	0.52445 <.0001	0.51664 <.0001	-0.28216 <.0001	-0.27323 <.0001	-0.0724 0.0371	-0.1572 <.0001	0.16805 <.0001	0.12331 0.0004	1	0.02771 0.4256	0.18443 <.0001	0.22127 <.0001	0.14119 <.0001
logging damage	0.10261 0.0031	0.07259 0.0367	-0.21901 <.0001	-0.1509 <.0001	-0.1617 <.0001	-0.06677 0.0546	0.19011 <.0001	-0.00556 0.8731	0.02771 0.4256	1	0.27052 <.0001	0.28782 <.0001	0.36858 <.0001
stumps ba	0.35676 <.0001	0.29173 <.0001	-0.66412 <.0001	-0.44666 <.0001	-0.50923 <.0001	-0.1734 <.0001	0.45492 <.0001	0.07235 0.0373	0.18443 <.0001	0.27052 <.0001	1	0.70992 <.0001	0.17269 <.0001
soil compact	0.35629 <.0001	0.28181 <.0001	-0.71983 <.0001	-0.50605 <.0001	-0.51413 <.0001	-0.18912 <.0001	0.51433 <.0001	0.03339 0.337	0.22127 <.0001	0.28782 <.0001	0.70992 <.0001	1	0.30157 <.0001
exp/dam roots	0.23034 <.0001	0.20402 <.0001	-0.17445 <.0001	-0.09683 0.0053	-0.16912 <.0001	-0.06427 0.0644	0.13852 <.0001	0.11409 0.001	0.14119 <.0001	0.36858 <.0001	0.17269 <.0001	0.30157 <.0001	1

* highlighted variables were removed from analysis

Table 3. Mean tree growth characteristics of *P. strobus* after treatment.

Treatment	N	DBH cm (Mean ± SE)	Height m (Mean ± SE)	LCR+ % (Mean ± SE)
clearcut	193	$22.6^{C} \pm 0.6$	$15.4^{D} \pm 0.2$	$33.7^{B} \pm 0.6$
control	350	$22.4^{C} \pm 0.5$	$20.3^{B} \pm 0.2$	$23.0^{D} \pm 0.5$
high density	94	$27.8^{B} \pm 0.9$	$17.5^{C} \pm 0.3$	$29.0^{C} \pm 0.9$
low density	135	$28.9^{B} \pm 0.7$	$17.5^{C} \pm 0.2$	$30.2^{C} \pm 0.7$
shelterwood	57	$44.8^{A} \pm 1.1$	$25.0^{A} \pm 0.4$	$42.4^{A} \pm 1.1$

Identical letters following the mean of a variable represent no significant difference (Tukey's HSD, $P > 0.05$)
+ live crown ratio

Table 4. Mean *P. strobus* tree damage and stump basal area after treatment.

Treatment	N	Logging Damage %+ (Mean ± SE)	BA Stumps and Snags m^2‡ (Mean ± SE)
clearcut	193	$0.0^{B} \pm 0.1$	$0.1^{C} \pm 0.0$
control	350	$0.0^{B} \pm 0.1$	$0.0^{D} \pm 0.0$
high density	94	$0.5^{A} \pm 0.1$	$0.9^{A} \pm 0.0$
low density	135	$0.7^{A} \pm 0.1$	$0.6^{B} \pm 0.0$
shelterwood	57	$0.3^{AB} \pm 0.1$	$0.6^{B} \pm 0.1$

Identical letters following the mean of a variable represent no significant difference (Tukey's HSD, $P > 0.05$)
+: % of lower bole damaged per tree by silvicultural practices
‡:basal area of stumps and year old snags within 12m of sample trees

Table 5. Mean basal area of residual forest trees after treatment.

Treatment	N	HW BA m^2/ha (Mean ± SE)	WP BA m^2/ha (Mean ± SE)
clearcut	20	$10.5^{A} \pm 0.9$	$16.0^{B} \pm 1.3$
control	20	$7.8^{A} \pm 0.9$	$23.6^{A} \pm 1.3$
high density	20	$0.1^{B} \pm 0.9$	$9.4^{C} \pm 1.3$
low density	20	$1.6^{B} \pm 0.9$	$14.7^{BC} \pm 1.3$
shelterwood	20	$2.6^{B} \pm 0.9$	$15.9^{B} \pm 1.3$

Identical letters following the mean of a variable represent no significant difference (Tukey's HSD, $P > 0.05$)

Table 6. Type III Analysis of Effects+ for Presence or Absence.

Effect	DF	Wald Chai-Square	Pr > ChiSq
site	4	16.90	0.002
diameter at breast height	1	0.18	0.6704
residual pine basal area / ha	1	9.40	0.0022
residual hardwood basal area / ha	1	4.47	0.0345
height	1	4.49	0.0339
crown class	1	0.72	0.396
live crown ratio	1	3.46	0.0629
logging damage to lower bole	1	9.56	0.002
basal area of pine stumps and year old snags	1	0.19	0.655
exposed or damaged roots	1	0.32	0.5714

+: hypothesis test for the variables contained in the binary logistic regression model

Table 7. Odds Ratio Estimate Table for the probability of presence or absence.

Odds Ratio Estimates					
Effect	Point Estimate	95% Wald Confidence Limits		Odds of Finding an Infested Tree in Shelterwood are:	
clearcut vs shelterwood	0.677	0.197	2.322	1.48[a]	Times the odds of finding one in clearcuts
control vs shelterwood	0.069	0.014	0.331	14.50[a]	Times the odds of finding one in control
high density vs shelterwood	1.079	0.309	3.765	0.93[a]	Times the odds of finding one in high density
low density vs shelterwood	1.022	0.331	3.150	0.98[a]	Times the odds of finding one in low density

a: 1/Point estimate = odds of finding an infested tree

Odds Ratio Estimates					
Effect	Point Estimate	95% Wald Confidence Limits		For Every Unit Increase[b] the Probability of Finding Infested Trees:	
residual pine basal area m^2/ha	0.071	0.013	0.385	Decreases by	-0.929 (92.90%)[c]
residual hardwood basal area m^2/ha	0.043	0.002	0.795	Decreases by	-0.957 (95.70%)[c]
Height m	1.125	1.009	1.255	Increases by	0.125 (12.50%)[c]
logging damage%	1.390	1.128	1.171	Increases by	0.390 (39.00%)[c]

b: Increase in m^2, m and % in relation to variable listed above
c: Point estimate -1 = increase or decrease in probability

Table 8. Type III Tests of Fixed Effects+ for Severity.

Effect	Num DF	Den DF	F Value	Pr > F
site	4	129	0.67	0.6126
diameter at breast height	1	129	0.48	0.4889
residual pine basal area / ha	1	129	0.08	0.7827
residual hardwood basal area / ha	1	129	1.11	0.2943
crown class	1	129	0.12	0.7329
height	1	129	1.41	0.2368
live crown ratio	1	129	2.53	0.1139
logging damage to lower bole	1	129	0.01	0.94
basal area of pine stumps and year old snags	1	129	7.48	0.0071
exposed or damaged roots	1	129	0.99	0.3206

+: hypothesis tests for the significance of the fixed effects contained in the lognormal distribution model

FIGURES

Figure 1. *Dendroctonus valens* pitch tubes at the base of a *P. strobus*.

Figure 2. *Dendroctonus valens* pitch tubes at the base of a *P. strobus*.

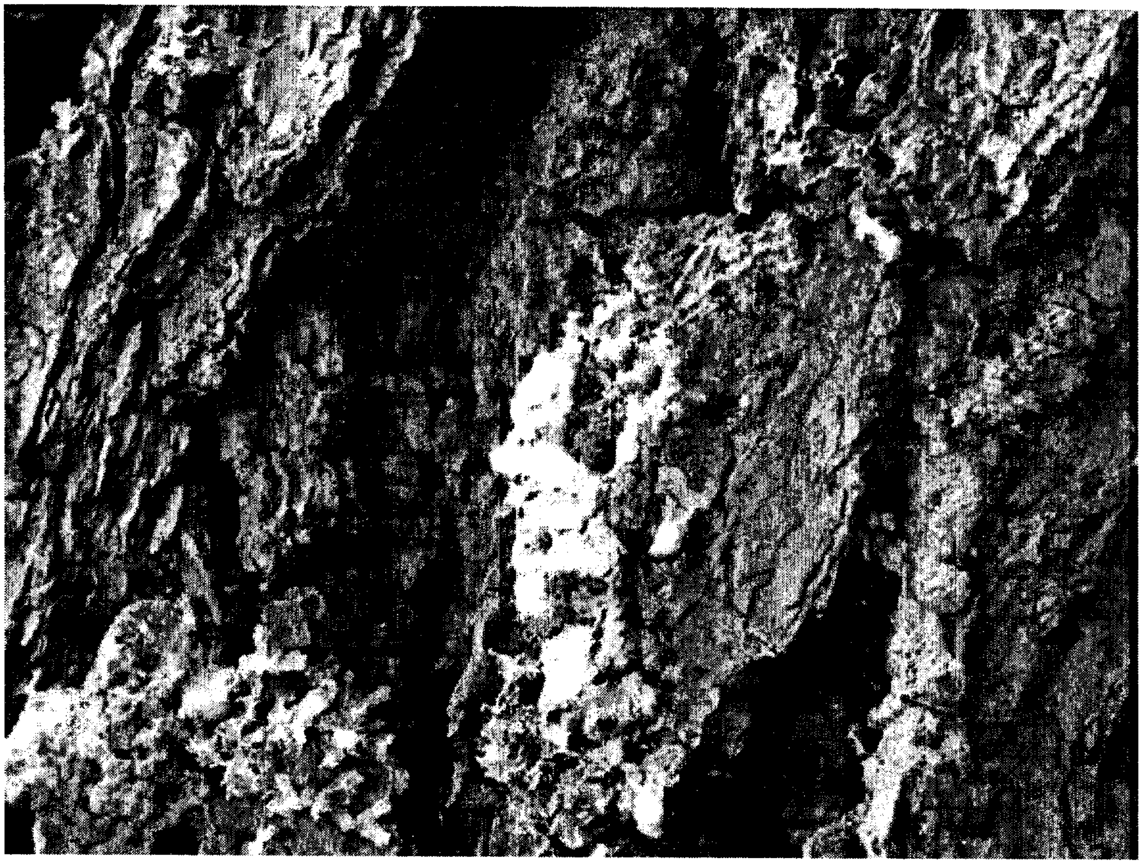

Figure 3. *Dendroctonus valens* pitch tubes and boring frass on a *P. strobus*.

Figure 4. *Dendroctonus valens* pitch tubes and streaking resin on a *P. strobus*.

Figure 5. Locus map of the Massabesic Experimental Forest, York County, Maine.

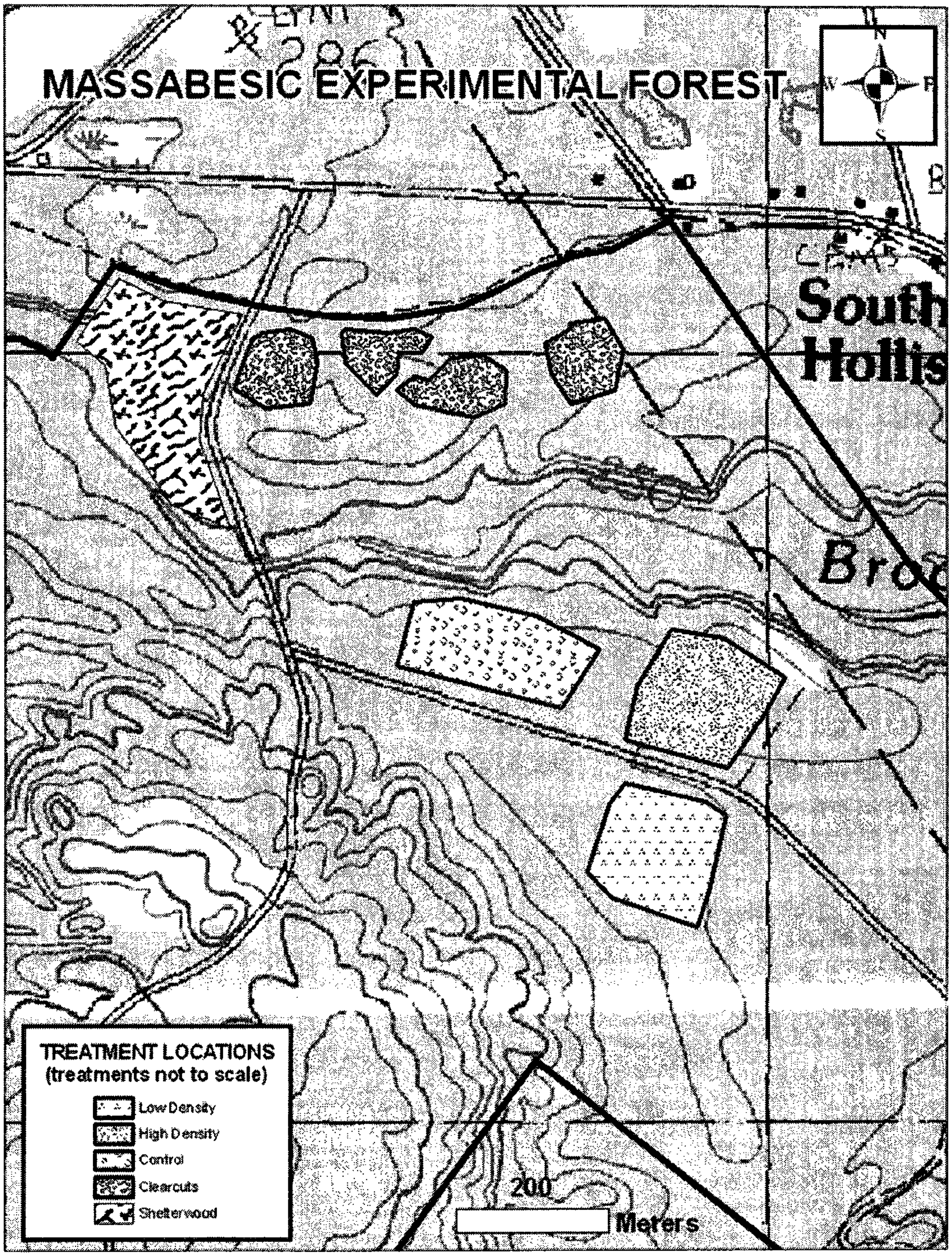

Figure 6. Treatment locations at the Massabesic Experimental Forest, York County, Maine.

Figure 7. Photograph of the shelterwood treatment at the Massabesic Experimental Forest.

Figure 8. Photograph of the shelterwood treatment at the Massabesic Experimental Forest.

Figure 9. Photograph of the clearcut treatment at the Massabesic Experimental Forest.

Figure 10. Photograph of the clearcut treatment at the Massabesic Experimental Forest.

Figure 11. Photograph of the high density removal treatment at the Massabesic Experimental Forest.

Figure 12. Photograph of the high density removal treatment at the Massabesic Experimental Forest.

Figure 13. Photograph of the low density removal treatment at the Massabesic Experimental Forest.

Figure 14. Photograph of the low density removal treatment at the Massabesic Experimental Forest.

Figure 15. Photograph of the control treatment at the Massabesic Experimental Forest.

Figure 16. Photograph of the control treatment at the Massabesic Experimental Forest.

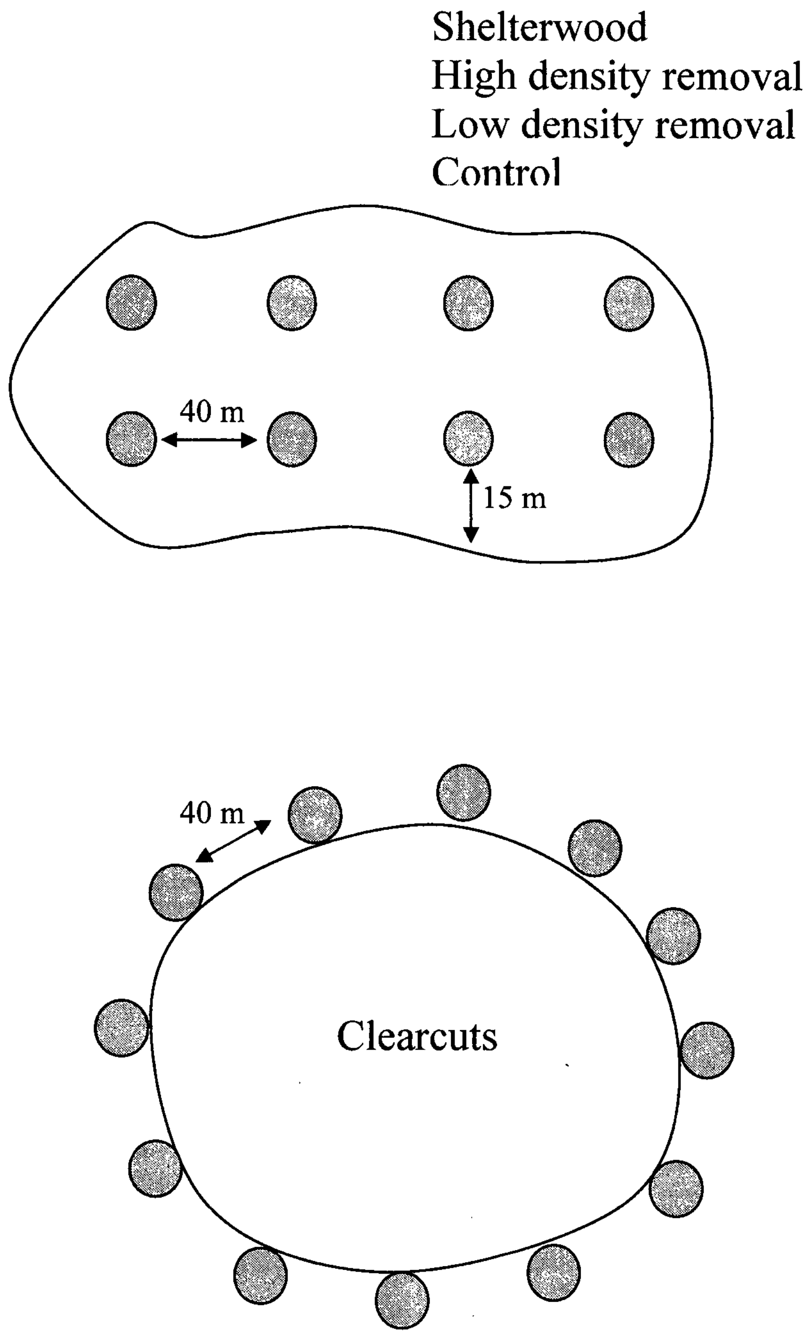

Figure 17. Sample plot layout.

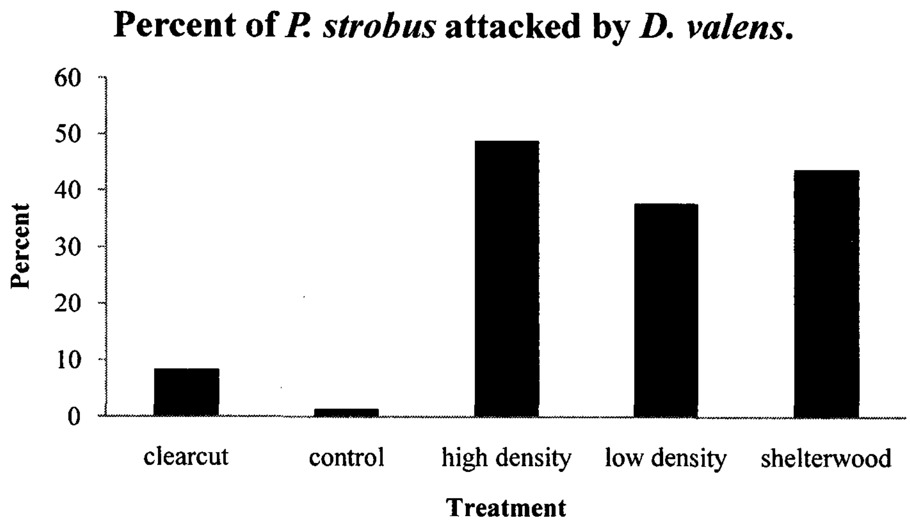

Figure 18. Percent of *P. strobus* attacked by *D. valens* after treatment.

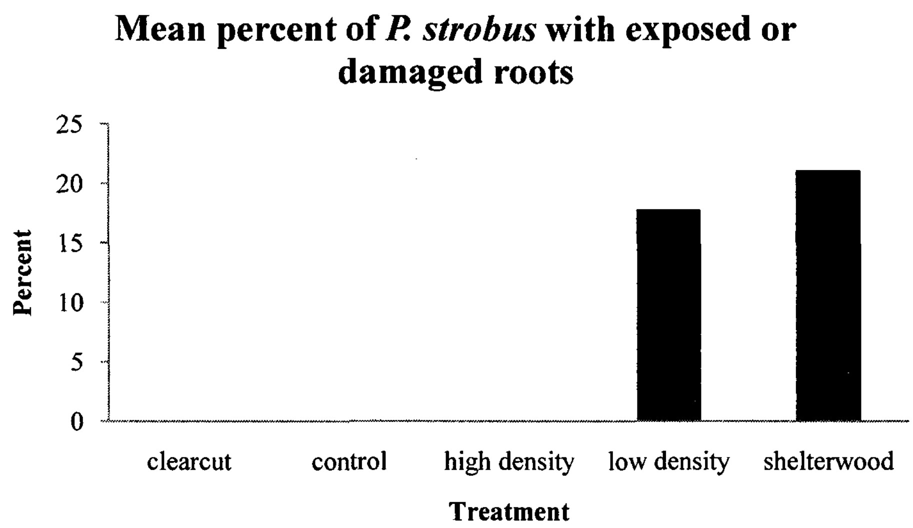

Figure 19. Mean percent of *P. strobus* with exposed or damaged roots after treatment.

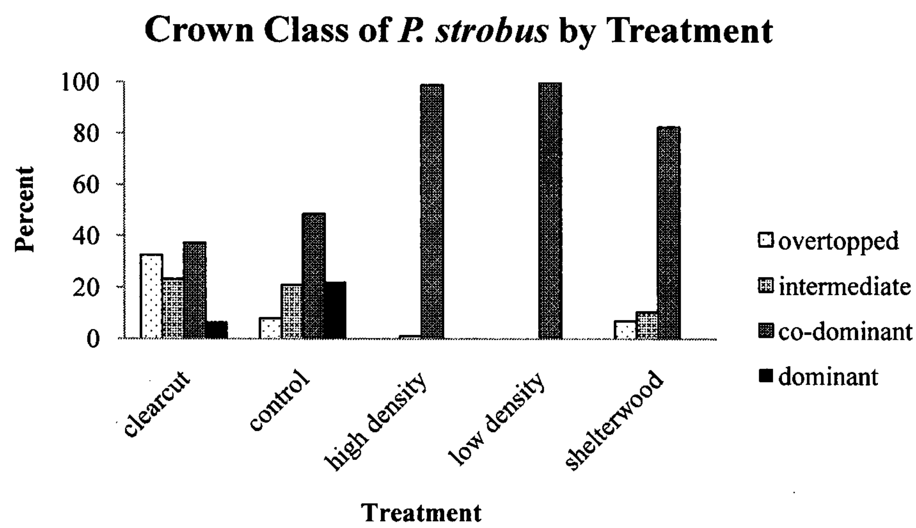

Figure 20. Crown class of *P. strobus* after treatment.