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Host Selection Behavior of the Douglas-fir Pitch Moth, *Synanthedon
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Intermediate Silvicultural Activities

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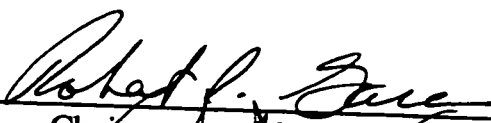
Jay Michael Johnson

A dissertation submitted in partial fulfillment
of the requirements for the degree of

Doctor of Philosophy

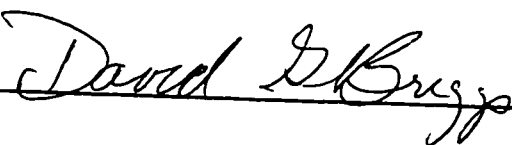
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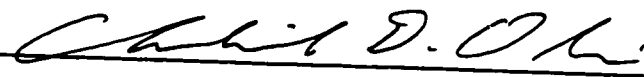
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Abstract

Host Selection Behavior of the Douglas-fir Pitch Moth, *Synanthedon novaroensis* (Hy. Edwards) (Lepidoptera:Sesiidae) Related to Intermediate Silvicultural Activities

by Jay Michael Johnson

Chairperson of the Supervisory Committee
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The Douglas-fir pitch moth (DFPM), *Synanthedon novaroensis*, is attracted to exudations of oleoresin and oviposits at wounds on the bole of host trees. Larvae then feed in subcortical regions of vigorously growing hosts. With the increase use of pruning in young stands of Douglas-fir, *Pseudotsuga menziesii* (Mirb.) Franco, the potential exists for the DFPM to create defects that would reduce the value of wood products and erode potential returns on this investment. Therefore, the objective of this study was to investigate the relationship between host selection behavior of the DFPM related to intermediate silvicultural activities such as pruning. Specific objectives of this study were to determine if DFPM demonstrates an ovipositional preference between: individual pruned Douglas-fir trees; clones of Douglas-fir; branch pruning wounds and wounds on the bole of Douglas-fir; pruning wounds made through the branch collar and wounds made outside the branch collar; and

made outside the branch collar; and wounds made during different seasons of the year.

A series of field experiments were conducted in young Douglas-fir stands in Western Washington from 1991-1997. The principal conclusions from these experiments were: DFPM host preference varies significantly between individual Douglas-fir trees; DFPM host preference varies significantly between clones of Douglas-fir; DFPM oviposits at wounds on the bole of a host more often than at wounds made outside the branch collar; DFPM oviposits significantly more often at pruning wounds made through the branch collar than at pruning wounds made outside the branch collar; and DFPM oviposits significantly more often at pruning wounds made in the spring than at pruning wounds made in summer, autumn, or winter.

TABLE OF CONTENTS

	Page
List of Figures	iii
List of Tables	iv
Introduction	1
Objectives	3
Background	5
Description and Life History of <i>Synanthedon novaroensis</i>	5
Insect Distribution and Hosts	10
Reproductive Isolation Between <i>S. novaroensis</i> and Other Sessids	13
Pruning Young Douglas-fir Stands	14
The Nature of Injury to Hosts by Pitch Moths	17
Materials and Methods	21
Study Sites	21
Intraspecific Host Preference by the DFPM	21
Clonal Preference for Oviposition by DFPM	23
Preference Between Branch Wounds and Bole Wounds for Oviposition Site by DFPM	24
DFPM Host Preference Related to Pruning Wounds Made Through and Outside the Branch collar	25
DFPM Host Preference Related to Season of Pruning	26
Results	27
Intraspecific Host Selection by DFPM for Oviposition Site	27

Host Selection by DFPM Related to Clonal Preference	27
Preference Between Branch Wounds and Bole Wounds for Oviposition Site by DFPM	32
DFPM Host Preference Related to Pruning Wounds Made Through and Outside the Branch Collar	32
DFPM Host Preference Related to Season of Pruning	37
Discussion	42
Implications for Intensive Management	47
Direction for Further Research	50
Conclusions	51
Bibliography	53

LIST OF FIGURES

Number	Page
1. The Douglas-fir pitch moth	6
2. Douglas-fir pitch moth nodules	9
3. Eclosion of adult Douglas-fir pitch moth	11
4. Radial cuts made through two branches from the same whorl of the same tree	19
5. Location of study sites	22
6. Percentage of trees with new DFPM ovipositions following a second pruning lift	29
7. Total number of DFPM ovipositions observed at the end of 1996 associated with stimulation wounds made in the spring of the year on a total of five trees in each of six clones	31
8. Percentage of trees with bole wounds, branch wounds, or no wounds which exhibited DFPM ovipositions	34
9. Percentage of trees with DFPM ovipositions at pruning wounds made through the branch collar and at pruning wounds made outside the branch collar	36
10. Number of DFPM ovipositions at pruning wounds made through the branch collar and at pruning wounds made outside the branch collar	39
11. Percentage of trees pruned in autumn, winter, spring, and summer with DFPM oviposition	41

LIST OF TABLES

Number	Page
1. The number of trees on which DFPM did and did not oviposit subsequent to executing a second pruning lift	28
2. Ovipositions by DFPM associated with stimulation wounds made in February 1996	30
3. Number of trees that received bole wounds, branch wounds, or no wounds on which DFPM did or did not oviposit	33
4. Number of trees pruned through the branch collar or outside the branch collar with, and without, ovipositions by DFPM	35
5. Number of ovipositions by DFPM associated with pruning wounds on trees with branches pruned through the branch collar and trees with branches pruned outside the branch collar	37
6. Number of trees pruned in autumn, 1995; winter, 1995-1996; spring, 1996; or summer, 1996 on which DFPM oviposited	40

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INTRODUCTION

The Douglas-fir pitch moth (DFPM), *Synanthedon novaroensis* (Hy. Edwards), is a pest of Douglas-fir, *Pseudotsuga menziesii* (Mirb.) Franco. Females are attracted to exudations of oleoresin and oviposit at or near wounds on the bole of host trees (Johnson 1993). Larvae then feed in subcortical regions of healthy trees for approximately two years. In the process of feeding, larvae sever resin canals which exude oleoresin. Larvae combine resin with their own excreta to form pitch nodules on the bole of the tree. The larvae maintain a tunnel within the pitch nodule within which they later pupate.

These behaviors are detrimental to silvicultural practices such as pruning in commercial forests. Larvae feeding around pruning wounds consume callus tissue which interferes with wound occlusion and delays the production of clear wood for the period of larval development. Additional delay in the production of clear wood occurs as occluding tissue envelopes the pitch nodule. This is further complicated by the fact that pruning is conducted early in the rotation of a commercial forest stand, and the investment in such an operation must often be carried over 55-60 or more years. As such, there is considerable risk associated with investment in pruning.

Moreover, as the commercial forest land base continues to decrease, intensive forestry practices such as pruning are expected to increase in the Pacific Northwest.

Intensive silvicultural practices will significantly increase stand volumes and values on a limited land base. However, pruning on an operational scale will increase resinous-attraction of hosts to DFPM and significantly increase the number of oviposition sites. The concomitant build up of DFPM populations could limit the benefits derived from silvicultural practices such as pruning.

Similarly, there is considerable risk associated with investments in seed orchards. Costs associated with development and maintenance of seed orchards are enormous. These costs are incurred well before the time of establishment and continue through the functional life of the orchard, often for over 50 years.

Risk to such a venture is elevated as attacks by DFPM increase. Typically, the seed manager determines which trees in the orchard he wants to produce a crop of seed. In the spring of the year, the trees that have been selected are wounded using a pruning saw. The saw is held in a horizontal plane against the bole of the tree and a cut is made from the bark through the phloem to the cambium. This wound extends slightly over half the circumference of the tree. Another wound is made a short distance above or below the first wound such that only the ends of both wounds overlap. Wounds made to trees in this fashion stimulate bud production. An increase in the number of stimulation wounds significantly increases the number of oviposition sites for DFPM and favors a build-up of the population. Further, the creation of stimulation wounds occurs frequently, as often as once every spring, which

favors chronic attacks by DFPM. Attacks by DFPM prevent the rapid occlusion of stimulation wounds which weaken the bole of the tree. Trees with stimulation wounds that have not fully occluded are more susceptible to windthrow and bole breakage at these weakened points from strong winds that occur infrequently during the fall and winter.

Risk to the sizable investments associated with seed tree orchards and operational pruning in commercial forests warrants investigation into the ability of the DFPM to become an economic pest. Since the potential for the DFPM to cause economic damage is related to changes in our management of Douglas-fir, a sound knowledge of the host selection behavior of the DFPM related to these changes will form a strong foundation for a successful integrated pest management (IPM) program for the DFPM.

Objectives

The overall objective of this study was to gain insights into the relationship between the host selection behavior of the DFPM and intermediate silvicultural operations which wound the host. Specific objectives were to:

1. Determine if the DFPM demonstrates a preference between individual pruned Douglas-fir trees for the purpose of oviposition;
2. Determine if DFPM demonstrates a preference between different clones of

Douglas-fir for oviposition;

3. Determine if DFPM demonstrates a preference between branch pruning wounds and wounds to the bole of Douglas-fir trees for oviposition;
4. Determine if DFPM demonstrates a preference between pruning wounds made through the branch collar over pruning wounds made outside the branch collar on Douglas-fir trees for oviposition;
5. Determine if DFPM demonstrates a seasonal preference between pruned Douglas-fir trees (pruned in the autumn, winter, spring, and summer) for oviposition.

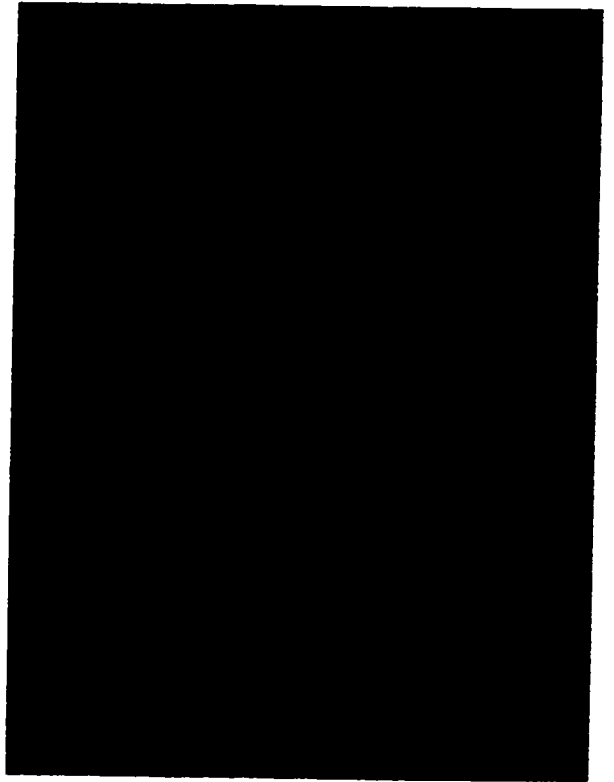
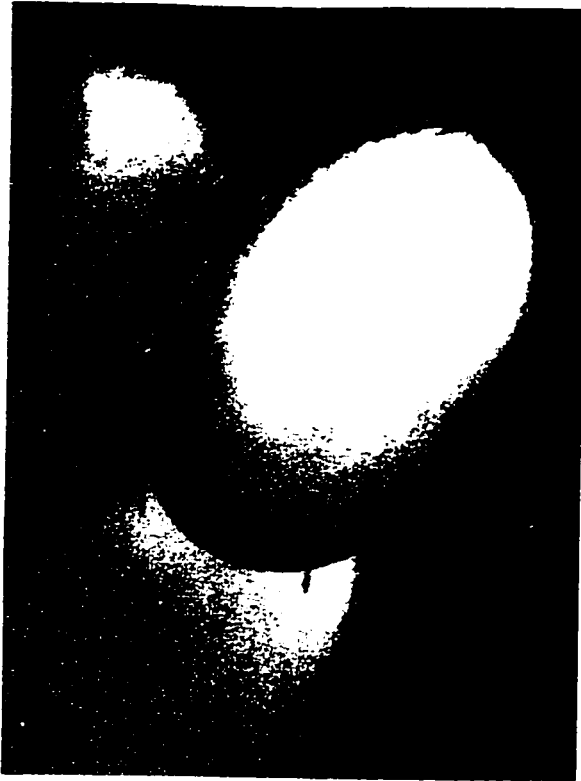
BACKGROUND

Description and Life History of Synanthedon novaroensis

The DFPM belongs to the family Sesiidae, the clearwing moths, which include serious pests of food crops, fruit orchards, ornamental landscapes, and forest plantations (Furniss and Carolin 1977). These moths are obligate borers whose endophagous larvae feed in limbs, boles, roots, vines, and galls, of trees, shrubs, and herbaceous plants (Furniss and Carolin 1977; Eichlin and Duckworth 1988). Adult sesiids are quickly distinguished from other moths by the partial or total absence of scales from their wings (Eichlin and Duckworth 1988). The coloration and appearance of these clearwing moths often mimic wasps and hornets (Eichlin and Duckworth 1988). Sesiids are active during the day, fly rapidly, and several species mimic the flight patterns of their hymenopterous role models (Brunner 1915).

External morphology and life cycle of the DFPM has been described by Brunner (1915), and later by Eichlin and Duckworth (1988). DFPM eggs are oblong and brownish (Figure 1). Larval bodies are whitish with a brown head (Figure 1). The darker intestines are visible through the skin. Full grown larvae measure 2.5 - 3.8 cm (1-1.5 in) long. Pupae are brown and possess transverse rows of spines on the dorsal portion of the abdominal segments (Figure 1). The pupae are quite active as the abdominal segments have strong musculature allowing the segments to move freely. Adult moths are black and their thorax mostly orange; the abdomen is

Figure 1. The Douglas-fir pitch moth: TOP LEFT, eggs; TOP RIGHT, larva; BOTTOM LEFT, pupa; BOTTOM RIGHT, adult.



ventrally orange, with dorsal orange bands (Figure 1). The regions around the head and legs also are orange. Antennae are brown black. Forewings are hyaline with margins and discal spot brownish black. Hindwings are hyaline. Females are about a third larger than males.

General emergence of the DFPM in the inland western United States occurs in June but begins as early as mid May (Brunner 1915). The DFPM begins to emerge as early as May along the west coast (Brunner 1915; Johnson 1993). The flight period in Washington is largely over by the end of August, however, males have been captured as late as September (Johnson 1993). After emergence, females emit a sex pheromone to attract males. Male DFPMs disperse throughout the daylight hours with peak flight occurring at midday (Johnson 1993).

Shortly after mating, females search for oviposition sites. The initial flight is characterized by rapid horizontal flight directed toward the bole of the host. Once the host is located, the female searches for an oviposition site on the bole of the host. At this stage, the female maintains a distance from the bole of 2.5 cm (1 in) to 5.0 cm (2 in) while searching for an oviposition site in a random fashion (personal observation).

After alighting on the host, the female probes with the tip of her abdomen for a suitable place to deposit her egg. Slightly over thirty eggs are laid by each female

(Brunner 1915). Females lay eggs singly, one egg per host often at the edge of a wound or on a smooth bark surface (Brunner 1915). Similarly, attacks by the sequoia pitch moth (SPM), *Synanthedon sequoiae* (Hy. Edwards), have been observed commonly around the edges of wounds (Weidman and Robbins 1947; Powers and Sundahl 1973). Attacks by SPM have also been observed at branch collars (Furniss and Carolin 1977).

The Douglas-fir pitch moth attacks trees with wounds that exude oleoresin, but not all wounds or wounded trees are selected for oviposition (Johnson 1993). In one study, the number of hosts attacked by DFPM increased in the second year following a pruning treatment, and several of the hosts previously attacked had multiple attacks (Johnson 1993). Moreover, the larger more vigorous trees were preferred for oviposition. Branches were removed from the boles of Douglas-fir trees in a pruning lift that effectively raised the height to the base of the live crown to 3 m (10 ft). Ovipositions were observed over the entire length of the bole that was pruned with the greatest number of ovipositions occurring at the middle of the pruning lift. However, oviposition was observed to be uniform around the bole of host trees (Johnson 1993).

Larvae emerge from their eggs and bore through the bark to begin feeding in the phloem. Larval activity is evidenced by the presence of pitch nodules (Figure 2). Pitch nodules contain resin mixed with excreta and are small and soft at first, but

Figure 2. Douglas-fir pitch moth nodules: TOP LEFT and TOP RIGHT, one year old nodules; BOTTOM LEFT, two year old nodule; BOTTOM RIGHT, old abandoned nodule from which an adult has emerged.



becoming larger and harder over a two-year developmental period (Eichlin and Duckworth 1988). Each larva lines its gallery in the pitch nodule with silk. When ready to emerge, the pupa uses the spines on its abdomen to push through the thin wall of pitch at the mouth of the tunnel. Eventually, the pupa wriggles a portion of its length through the pitch mass and the delicate adult emerges without coming in contact with resin (Figure 3). Douglas-fir pitch moths also pupate outside of the pitch nodule just under the bark of the host (personal observation).

Reports are varied regarding the length of time the DFPM requires to develop from egg to adult. Brunner (1915) indicates that feeding continues for three years and sometimes for four years at higher elevations. Eichlin and Duckworth (1988) report that the life cycle takes two years. Another closely related clearwing moth, the sequoia pitch moth (SPM), has been observed to take two years to fully develop (Brunner 1914). However, SPM has been observed to complete development in a single year (Campbell and Barstow 1976). I have observed DFPM emergence near Cumberland, Washington, and larval development commonly requires two years but ranges from one to three years.

Insect Distribution and Hosts

Sesiids are worldwide in distribution with over a thousand described species (Duckworth and Eichlin 1977). One hundred twenty three species of clearwing

Figure 3. Eclosion of adult Douglas-fir pitch moth: TOP LEFT, pitch nodule with pupa extended beyond mouth of tunnel; TOP RIGHT, adult breaking through pupal case MIDDLE LEFT and MIDDLE RIGHT, adult extracting itself from the pupal case; BOTTOM LEFT, wings enlarging; BOTTOM RIGHT, fully developed adult.



moths are recognized in America north of Mexico (Eichlin and Duckworth 1988). Only three species in this region are known to feed exclusively on Pinaceae species (Eichlin and Duckworth 1988).

The pitch mass borer, *Synanthedon pini* (Kellicott), is found in the Midwest, the Appalachian region, Southeastern Canada, and south along the Atlantic Coast (Eichlin and Duckworth 1988). The known hosts for *S. pini* include: eastern white pine, *Pinus strobus* Linnaeus; Norway spruce, *Picea abies* (Linnaeus) Karst.; white spruce, *P. glauca* Voss; jack pine, *Pinus banksiana* Lambert; and Scots pine, *P. sylvestris* Linnaeus (Eichlin and Duckworth 1988).

The Sequoia pitch moth, *S. sequoiae*, occurs from northern British Columbia south along the Pacific Coast to Monterey County, California, and in the Rocky Mountains (Eichlin and Duckworth 1988). Recorded hosts of Sequoia pitch moth include: lodgepole pine, *Pinus contorta* Douglas ex. Loudon; sugar pine, *P. lambertiana* Douglas; ponderosa pine, *P. ponderosa* Douglas ex. P. and C. Lawson; Bishop pine, *P. muricata* D. Don; and Monterey pine, *P. radiata* D. Don (Eichlin and Duckworth 1988). Furniss and Carolin, (1977), include Douglas-fir among the hosts of this moth. Observations of Sequoia pitch moth activity at the Eddy Arboretum, near Placerville, California, have shown that numerous species of exotic and native pines are suitable hosts for this insect (Weidman and Robbins 1947).

The DFPM ranges in distribution from Alaska to northern California and east from

the Pacific coast to Montana (Eichlin and Duckworth 1988). Hosts of this moth include: Douglas-fir; lodgepole pine; western white pine, *Pinus monticola* Douglas ex. D. Don; Sitka spruce, *Picea sitchensis* (Bongard) Carriere; and Engelmann spruce, *P. engelmannii* Parry ex. Engelmann (Eichlin and Duckworth 1988).

Reproductive Isolation Between Synanthedon novaroensis and Other Sessiids

Sympatric species use isolating mechanisms to maintain species integrity. Temporal, geographic and mating segregation, in association with different vegetation strata, serve as isolating mechanisms (Greenfield and Karandinos 1979). The DFPM and Sequoia pitch moth clearly overlap in geographic distribution. These moths are known to share at least one common host, lodgepole pine, and possibly two others, Douglas-fir and ponderosa pine. Both moths share similar diel and seasonal flight periods, but each has a different sex pheromone, which effectively maintains species separation. In fact, male Douglas-fir pitch moths are attracted to the compound (Z,Z)-3,13-octadecadien-1-ol-acetate (ZZ-ODDA) (Eichlin and Duckworth 1988), while sequoia pitch moth males respond to (Z,Z)-3,13-octadecadien-1-ol-alcohol (ZZ-ODDOH) (Nielsen et.al. 1978).

Other sessiids are attracted to the same compound as the DFPM in Western Washington. *Synanthedon culiciformis*, and *Sesia tibialis*, have also been collected in wing traps baited with ZZ-ODDA (Johnson 1993). However, these species are

isolated temporally. *Synanthedon culiciformis* responds to ZZ-ODDA early in the spring, followed by DFPM beginning in May and continuing through the summer, and then *Sesia tibialis* in the late summer (Johnson 1993).

Pruning Young Douglas-fir Stands

Douglas-fir retain branches from 75 to over 100 years (Kotok 1951; Paul 1947). Accordingly, old-growth trees (>200 yrs-old) have been the main source of high grade, knot-free lumber. However, there is a limited supply of this material, primarily because the supply of old-growth trees is diminishing, and harvesting of available sources is restricted or protected. The situation is further complicated by the economic necessity of managing commercial forest stands on 40-80 year rotations. Douglas-fir, grown in short rotations, will not have had sufficient time to self prune. Nevertheless, premium prices received for clear lumber together with the ever increasing scarcity of this resource argue strongly in favor of pruning on an operational scale (Cahill et al. 1986).

Pruning should be conducted early within a rotation in order to maximize amount of clear wood that can be produced and capture the greatest value. Modern veneer mills, with chuck-less peeling lathes, utilize a high percentage of the log volume, small trees, and leave small peeler cores. Thus, at a rotation age of 50-60 years, Douglas-fir trees will be merchantable because of new technology and efficient

milling practices.

Trees selected for pruning will be about 10.2-15.3 cm (4-6 in) DBH and two approaches have been suggested for determining the maximum height at which such trees should be pruned. One approach specifies that no more than one third of the lower live crown should be removed (Cahill et. al. 1986). The other strategy requires that pruning not exceed one half the total tree height. Production of clear 4.9 m (16 ft) butt logs, plus 0.6 m (2 ft) for stump and saw kerf, would require a pruning lift to 5.5 m (18 ft). Using the latter rule of thumb, stands ready for pruning should contain 11 m (36 ft) tall trees.

Another reason for pruning early in the stand rotation is to remove branches while they are still small in cross section. Large pruning wounds take longer to occlude than smaller ones and, more importantly, the longer a pruning wound takes to seal, the less clear wood is produced (Petruccio et al. 1997). In addition, the longer a wound takes to occlude, the longer the tree is susceptible to attack by pathogens and insects. For these reasons, pruning in two or more lifts is advisable. This approach would allow managers to enter stands earlier in the rotation and produce more clear wood.

One strategy for removing tree branches stipulates that the cut be made outside the branch collar (Shigo 1989). Pruning cuts made in this fashion will maintain the

protection zone within the branch collar and provide a barrier to infection by pathogens. Another perspective holds that cuts made through the branch collar or flush to the bole occlude at a faster rate than cuts made outside the branch collar (Helmert 194; Childs and Wright 1956). Thus, a smaller branch stub results in a smaller defect core, clear wood is produced sooner, and a greater volume of clear wood is obtained over the same rotation. Damage incurred from pathogens that infect the tree through the compromised protection zone would be limited in extent to the small defect core by the strong barrier formed at the time of wound occlusion. Losses in revenue due to diseased defect cores would be more than compensated for by increase in grade and value of greater volumes of clear wood that results.

Pruning commercial stands of Douglas-fir can be conducted throughout the year. However, bark slips easily in the spring when the sap is flowing. For this reason, pruning in the spring with a hatchet, machete, or similar tool is discouraged. Even when using a pruning saw, care must be exercised to prevent peeling or stripping of bark along the bole of the tree. A safer approach is to use pruning shears when pruning is conducted in the spring.

Death of cambium may occur around the edges of the pruning wounds. The extent of cambium dieback has been shown to vary with the time of year that branch wounds are made (Shigo 1991). Substantial dieback is associated with pruning wounds made in autumn. Extensive dieback of cambium increases the length of time

required for wounds to occlude. Thus, reduced cambium dieback and more rapid wound occlusion is favored when pruning is done during the dormant period, or in the summer, when wood and inner bark formation is at a peak.

Clearly, pruning can be conducted in a manner that promotes rapid wound occlusion by the tree and maximize clear wood production. However, pruning on an operational scale attracts DFPM to the treated stands and significantly increase the number of oviposition sites. This change from historical forest management practices will increase activity of DFPM in pruned stands. Increased damage from DFPM will frustrate the objective of pruning which is increased clear wood production and elevate the status of the DFPM to one of economic pest.

The Nature of Injury to Hosts by Pitch Moths

Feeding activity of the DFPM tends to be localized around the oviposition site (Furniss and Carolin 1977). Injury caused by this feeding has not been viewed as a direct threat to the life of its host. In stands where moths are active, the number of these insects is seldom high (Brunner 1915). Consequently, no control measures have been warranted. One reason why populations of DFPMs have not reached epidemic levels is the scarcity of wounds that attract ovipositing females. In natural, unmanaged forests, resin exudation on from boles of trees result from antler rubs by deer and elk, girdling by bear and porcupine, drilling by sapsuckers, and resinous

resulting from fungal activity. Abiotic factors causing wounds include lightning, landslides, and fire. At times, wounds produced by these factors can be numerous but in most cases wounds are isolated and infrequent.

Operational pruning will significantly increase the oviposition sites for the DFPM and favor a build-up in the population levels of this pest. Severe outbreaks of the pitch moths can kill trees. Direct mortality could result when numerous larvae feeding in an individual tree effectively girdle the host. Indirect mortality occurs when strong winds break the tree at the point where larval activity has sufficiently weakened the bole (Duncan 1996). In addition, attacks that continue over several years can weaken trees to the point where they lose competitive advantage to neighboring trees (Brunner 1914).

Even when attacks are few in number, larval feeding activity will cause sapwood defects. For example, a cross section was cut from the bole of a Douglas-fir which had been pruned ten years earlier. This section of the bole contained a whorl of branches. Radial cuts were made through each of two branches in this whorl. One branch had been attacked by DFPM as evidenced by the presence of a pitch nodule. Examination of the radial cuts revealed that the branch which was pruned and was without DFPM attack had occluded and was already producing clear wood (Figure 4). The pruning wound, subsequently attacked by DFPM, revealed an accumulation of bark and pitch beyond the branch stub and had still not produced clear wood ten

Figure 4. Radial cuts made through two branches from the same whorl of the same tree: TOP, pruning wound without attack by Douglas-fir pitch moth occluded five years after pruning; BOTTOM, pruning wound attacked by Douglas-fir pitch moth exhibiting included bark and resin and still not occluded ten years following treatment.



years later (Figure 4). In effect, less clear wood volume can be harvested at rotation age because of DFPM attacks. A continual problem results because the bark, at the site of previous pitch moth attack, is left in a condition that attracts additional DFPM attack (Brunner 1914). Thus, even after pruning wounds have occluded, attacks by pitch moths may continue. If pitch moth activity continues over successive years, less clear wood will be produced, and the investment in pruning may not be recaptured at rotation age.

MATERIALS AND METHODS

Study Sites

Field studies were conducted at four locations in western Washington (Figure 5). Two studies were located in Section 16, Township 21 North, Range 07 East, W.M. near Cumberland, Washington. This land was owned by the Municipality of Metropolitan Seattle (Metro) at the time of establishment and subsequently was acquired by the Washington State Department of Natural Resources (WA DNR). Another study was located on Plum Creek Timber Company land southeast of Johnson's Corner near Ravensdale, Washington. Additional study sites were located in the Mashel Flats species trial at Charles Lathrop Pack Demonstration Forest owned by the University of Washington near LaGrande, Washington and the Weyerhaeuser Seed Orchard near Rochester, Washington.

Intraspecific Host Preference by the DFPM

It was hypothesized that pruned trees, subsequently attacked by DFPM, would be preferentially selected by DFPM for oviposition following a second pruning compared to pruned trees which were not selected for oviposition by DFPM after these trees were pruned a second time. The null hypothesis for this study assumed no difference in host preference by DFPM between previously attacked trees and trees without attacks. In order to test this hypothesis, 1200 Douglas-fir trees, breast-

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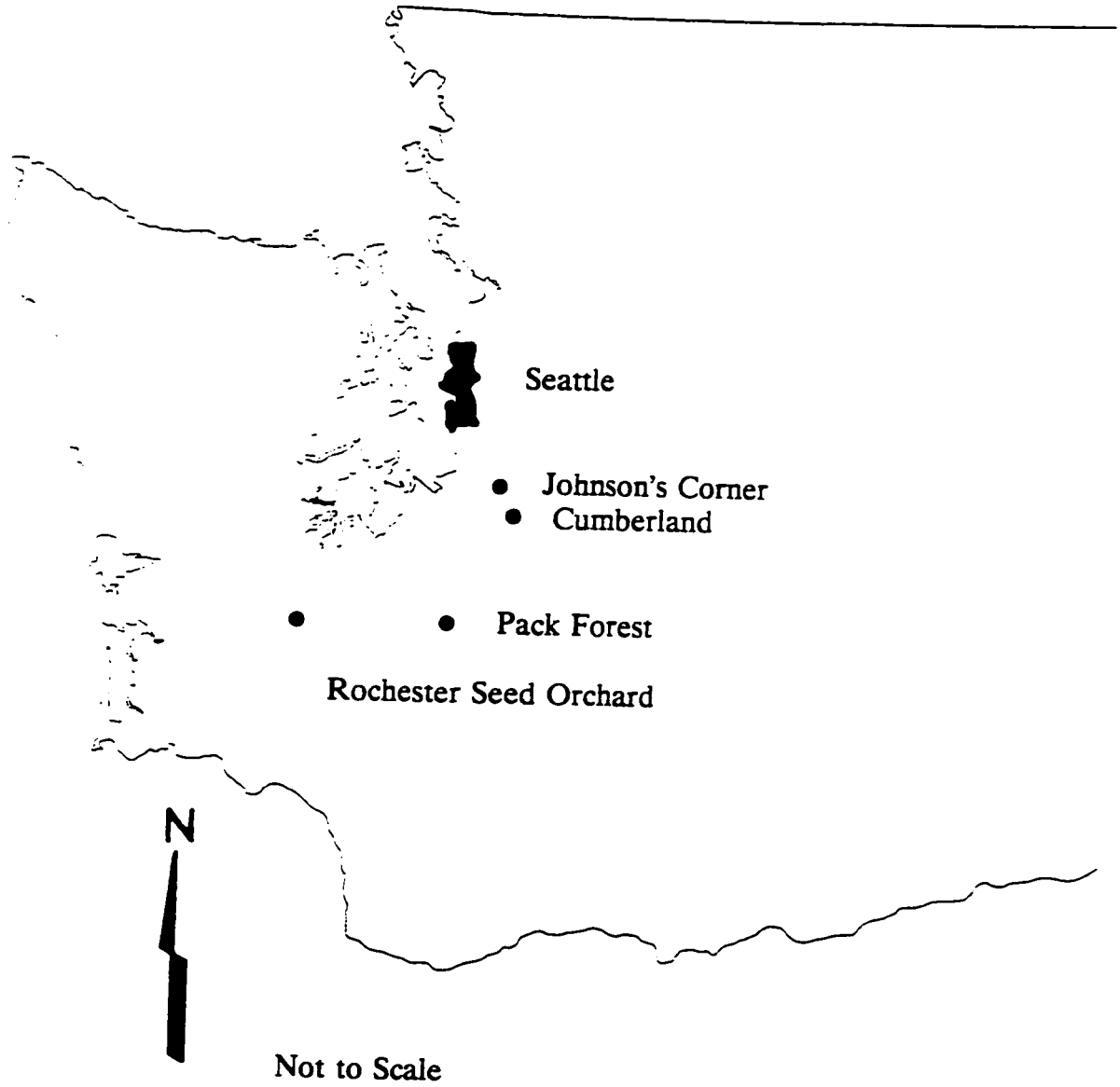


Figure 5. Location of Study Sites.

height-age 14 years, were tagged at the study site near Cumberland in 1991. Six hundred of these trees were randomly selected for treatment and pruned to a height of 3 m (10 ft) as part of an investigation into the oviposition patterns of the DFPM (Johnson 1993). The other 600 trees served as controls. Four years following the initial pruning lift, 118 of the 600 pruned trees had been attacked by DFPMs. In May of 1995, the 118 trees pruned initially in 1991 and subsequently attacked by DFPM were given a second pruning lift to 5.5 m (18 ft). One hundred and eighteen trees pruned in 1991 but not attacked by DFPM 4 years following treatment were also given a second pruning lift at the same time. In the spring of 1996, this study site was inadvertently thinned by the new landowner. Seventy-five study trees were cut leaving 84 trees in the previously attacked population and 77 trees in the previously unattacked population. Although the residual populations were unequal in size, a sufficient number of trees remained in each population to permit a comparison of differences in the level of DFPM attack between populations. Total number of trees with DFPM attacks as evidenced by the presence of pitch nodules on that portion of the bole of each tree pruned in 1995 was recorded for the 2 year period from 1995 through 1996. A Z-test for equal proportions was employed for the analysis of this test of homogeneity (Zar 1984).

Clonal Preference for Oviposition by DFPM

It was hypothesized that DFPM would demonstrate a ovipositional preference for

one or more clones of Douglas-fir trees. The null hypothesis tested assumed that there was no preference by DFPM between clones of Douglas-fir for oviposition. In order to test the null hypothesis, trees from the Longview block of Rochester seed orchard that were wounded in February of 1996 to stimulate an increase in bud production were identified and recorded. Stimulation wounds made in February 1996 were distinguished from wounds made in previous years by inserting red thumb tacks at the ends of the current years wound. Five trees from each of 6 clones were monitored for evidence of ovipositions by DFPM at the end of the growing season. Clones with fewer than 5 wounded individuals were excluded from this study. Likewise, clones with greater than 5 wounded individuals were excluded from this study. The null hypothesis was tested with a goodness-of-fit using the Chi-square statistic (Zar 1984).

Preference Between Branch Wounds and Bole Wounds for Oviposition Site by DFPM

It was hypothesized that DFPM would demonstrate a preference between branch wounded trees, bole wounded trees, and trees without wounds for ovipositions. The null hypothesis for this study was that the DFPM would demonstrate no difference in host preference between bole wounded trees, branch wounded trees, and trees without wounds. In order to test the null hypothesis for this study, three hundred trees, average breast-height-age approximately 12 years, were tagged with aluminum tags and nails in the late spring of 1995. Treatments were randomly assigned. In

one treatment, 8 branches were removed from each of 100 trees at a point roughly 1.3 m (4.5 ft) above the ground. Pruning loppers were used to sever the limbs from the trees at a point just outside the branch collar. In a second treatment, 8 wounds were made to the bole on each of an additional 100 trees again at a point roughly 1.3 m (4.5 ft) above the ground. Bole wounds were made using a steel leather punch 1.27 cm (0.5 in) in diameter, to approximate the size wound made in the branch pruning treatment. The remaining 100 trees served as controls. Preference was determined comparing the difference in total number of ovipositions as evidenced by the presence of pitch nodules between treatments recorded over a period of 2 years. The Chi-square statistic was used in the analysis of this goodness-of-fit test (Zar 1984).

DFPM Host Preference Related to Pruning Wounds Made Through the Branch Collar and Outside the Branch Collar

It was hypothesized that the DFPM would demonstrate an ovipositional preference between trees pruned through the branch collar and trees pruned outside the branch collar. The null hypothesis for this study assumed that there was no preference by DFPM between trees with pruning wounds made through the branch collar and trees with pruning wounds made outside the branch collar for oviposition. Four hundred, 19 year old Douglas-fir trees were tagged with aluminum nails and tags in the spring of 1996 at Pack Forest in the Mashel Flats unit. Treatments were randomly assigned.

Trees were pruned to a height of 2.7 m (9 ft) using a small chainsaw. Two hundred trees were pruned outside the branch collar and 200 trees were pruned through the branch collar. Total number of pitch nodules per tree was recorded in the fall of 1996. Preference for wound type was determined by comparing the number of trees attacked by DFPM in each treatment. The total number of DFPM attacks between treatments was also analyzed. In both cases, the Chi-square statistic was used in goodness-of-fit tests (Zar 1984).

DFPM Host Preference Related to Season of Pruning

It was hypothesized that the DFPM would demonstrate an ovipositional preference between trees pruned during different seasons of the year. The null hypothesis for this study assumed that there was no difference in ovipositional preference by DFPM between trees pruned during different seasons of the year. Numbered aluminum tags were nailed to four hundred, 14 year old, Douglas-fir trees at 3.1 m (4.5 ft) above the ground in the fall of 1995 at the Johnson's Corner site. Pruning treatments were made in the fall of 1995, winter of 1995-1996, spring of 1996, and summer of 1996. One hundred trees were pruned to a height of 2.7 m (9 ft) at each entry. Branches were removed using pruning loppers. Branches were cut at a point just outside the branch collar. The number of ovipositions as evidenced by the presence of pitch nodules was recorded in the fall of 1996. The Chi-square statistic was used in the analysis of this goodness-of-fit test (Zar 1984).

RESULTS

Intraspecific Host Selection by DFPM for Oviposition Site

Douglas-fir pitch moth attacked a significantly greater number of trees from among the eighty-four trees which were attacked by DFPM following the first pruning lift in 1991, than from the population of seventy-seven trees with no attacks by DFPM following the first pruning lift, after both populations were given a second pruning lift in 1995 (Table 1). In fact, 10.7% of the previously attacked trees were attacked again when given a second lift compared to 3.9% of the previously unattacked trees that were attacked for the first time when given a second lift (Figure 6).

Host Selection by DFPM Related to Clonal Preference

A comparison between 6 Douglas-fir clones in the Longview block at the Rochester seed orchard, each with 5 individual trees wounded in February of 1996, showed a significant difference in the level of attacks between clones (Table 2). In fact, the total number of DFPM attacks per clone ranged from a high of 15 for clone 301 to a low of 2 for clone 243 (Figure 7). Freeman-Tukey deviates obtained for this study indicate clone 301 was attacked by DFPM more often than would be expected while clone 243 was attacked by DFPM less often than would be expected (Table 2).

TABLE 1. The number of trees on which DFPM did and did not oviposit subsequent to executing a second pruning lift from a height of 3 m (10 feet) above the ground to 18 feet above the ground. Trees that received the second pruning lift were previously pruned to a height of 10 feet and either attacked or not attacked by DFPM in the four years following the initial pruning lift.

POPULATION	NUMBER OF TREES ON WHICH DFPM DID OVIPOSIT	NUMBER OF TREES ON WHICH DFPM DID NOT OVIPOSIT	Z STATISTIC	P VALUE
PREVIOUSLY ATTACKED	9	75	Z=1.645	P=0.05
PREVIOUSLY NOT ATTACKED	3	74		

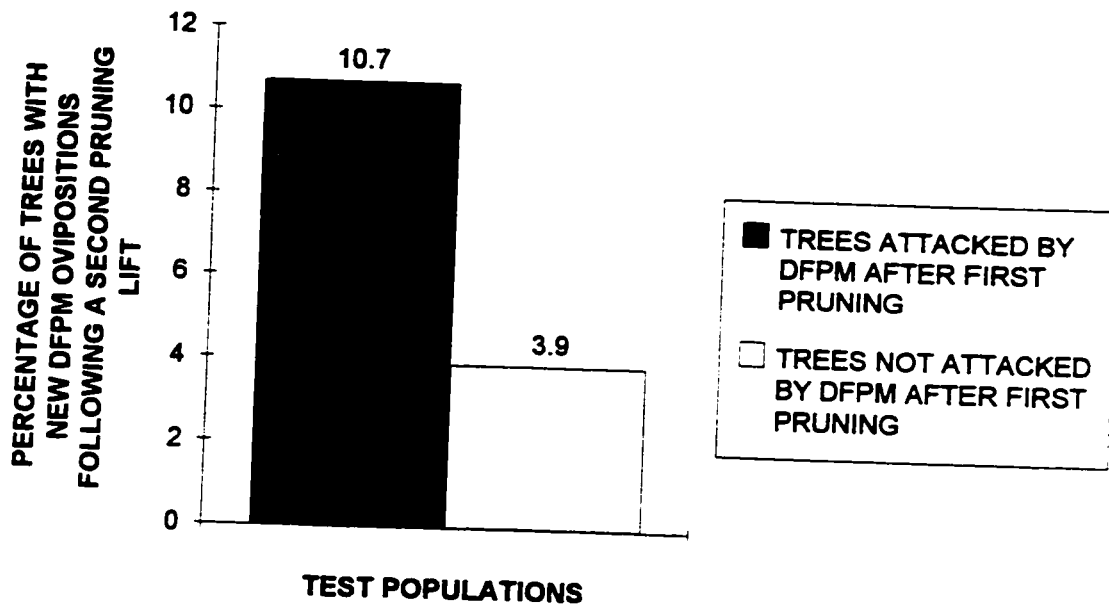


Figure 6. Percentage of trees with new DFPM ovipositions following a second pruning lift.

Table 2. Ovipositions by DFPM associated with stimulation wounds made in February 1996. Values reflect the total number of ovipositions on five trees per clone of Douglas-fir monitored.

CLONE	NUMBER OF OVIPOSITIONS BY DFPM	CHI-SQUARE STATISTIC	P VALUE	FREEMAN-TUKEY DEVIATES *
301	15	$\chi^2_5 = 16.99^{**}$	$P < 0.005$	+2.3052
231	11			+1.2129
218	9			+0.5945
223	5			-0.8822
233	3			-1.8357
243	2			-2.4215

* Freeman-Tukey deviates (residuals) were calculated for the subsequent inspection of data following rejection of the null hypothesis for this goodness-of-fit test. If a residual is obtained which is both large, absolute value greater than two, and positive, then the observed frequency for the associated category is larger than expected. Residuals which are large and negative indicate that the observed frequency for the associated category is less than expected. The probability of a residual with an absolute value greater than two is equal to 0.0455.

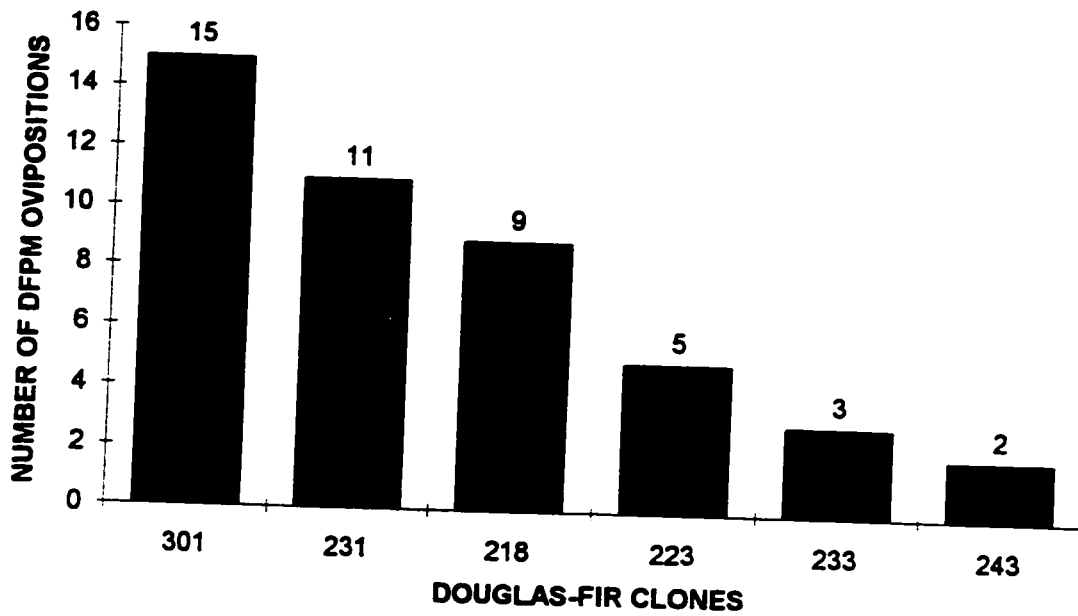


Figure 7. Total number of DFPM ovipositions observed at the end of 1996 associated with stimulation wounds made in the spring of the year on a total of five trees in each of six clones.

Preference Between Branch Wounds and Bole Wounds for Oviposition Site by DFPM

A significant difference in the number of trees attacked by DFPM was found between trees with branches wounded outside the branch collar, bole wounded trees, and control trees (Table 3). Standardized residuals for this test indicate that fewer control trees than were expected were attacked by DFPM and that more bole wounded trees were attacked by DFPM than expected. In fact, 1.75 times as many bole wounded trees were attacked as branch wounded trees (Figure 8). No control trees were attacked by DFPM.

DFPM Host Preference Related to Pruning Wounds Made Through and Outside the Branch Collar

A significantly greater number of the Douglas-fir trees pruned through the branch collar were attacked by DFPM than trees pruned outside the branch collar (Table 4). In fact, 116 of the 200 Douglas-fir trees pruned through the branch collar were attacked by DFPM compared to 48 of the 200 Douglas-firs pruned outside the branch collar (Figure 9). Approximately 2.4 times as many trees pruned through the branch collar were attacked by DFPM as trees pruned outside the branch collar by the end of the first growing season.

The total number of attacks by DFPM was also significantly greater on trees pruned

Table 3. Number of trees that received bole wounds, branch wounds, or no wounds on which DFPM did or did not oviposit.

TREATMENT	NUMBER OF TREES ON WHICH DFPM OVIPOSITED	NUMBER OF TREES ON WHICH DFPM DID NOT OVIPOSIT	CHI-SQUARE STATISTIC	P VALUE
BOLE WOUNDS	14	86	$\chi^2_2 = 14.525^{**}$	$P < 0.001$
BRANCH WOUNDS	8	92		
CONTROL	0	100		

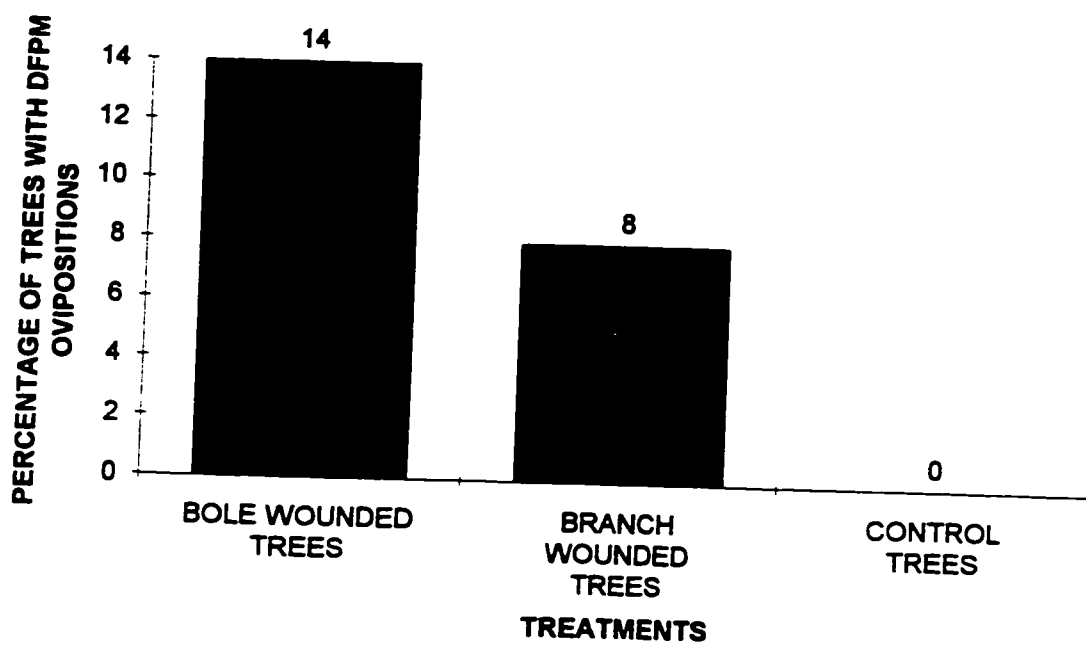


Figure 8. Percentage of trees with bole wounds, branch wounds, or no wounds which exhibited DFPM ovipositions.

Table 4. Number of trees pruned through the branch collar or outside the branch collar with, and without, ovipositions by DFPM.

TREATMENT	NUMBER OF TREES ON WHICH DFPM OVIPOSITED	NUMBER OF TREES ON WHICH DFPM OVIPOSITED	CHI-SQUARE STATISTIC	P VALUE
PRUNED THROUGH BRANCH COLLAR	116	84	$\chi^2_c = 34.595^{**}$	$P < 0.001$
PRUNED OUTSIDE BRANCH COLLAR	48	152		

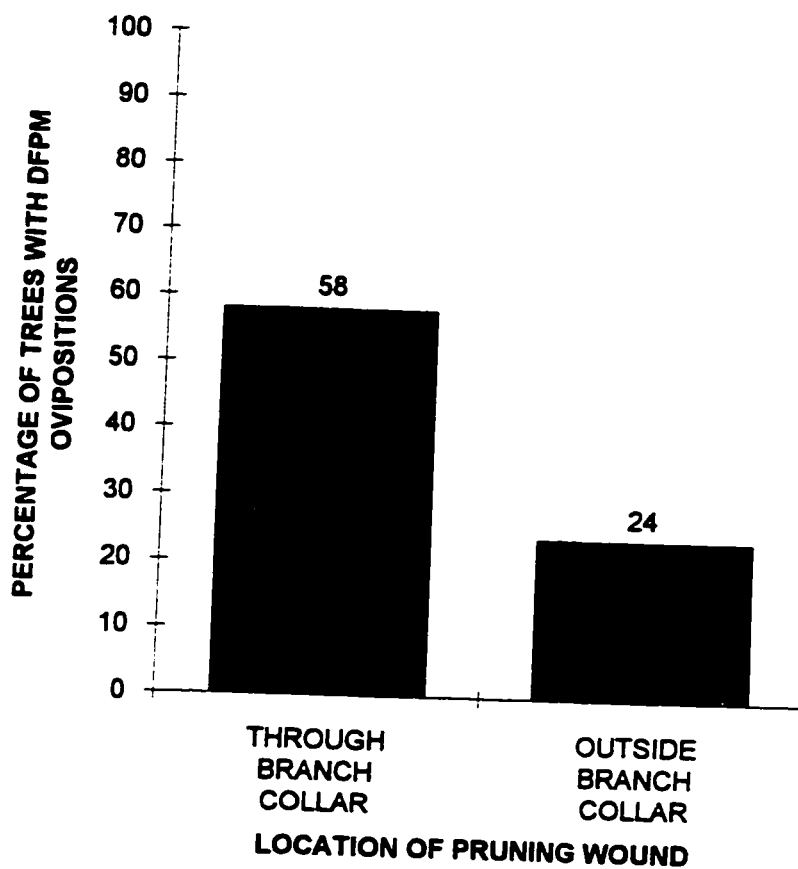


Figure 9. Percentage of trees with DFPM ovipositions at pruning wounds made through the branch collar and at pruning wounds made outside the branch collar.

through the branch collar compared to trees pruned outside the collar (Table 5). In fact, 291 ovipositions were observed on the 116 trees pruned through the branch collar compared to 73 ovipositions on the 48 trees pruned outside the branch collar (Figure 10). Trees pruned through the branch collar were attacked approximately 4 times as often as trees pruned outside the branch collar.

DFPM Host Preference Related to Season of Pruning

A significant difference in the number of hosts attacked by DFPM was observed between Douglas-fir trees pruned at different seasons of the year (Table 6). At the Johnson's Corner study site, the number of trees attacked by DFPM ranged from 13 trees pruned in the spring to one tree among those trees pruned in the winter (Figure 11). Freeman-Tukey deviates for this test indicate that a greater number of the trees pruned in the spring were attacked by DFPM than would be expected and that fewer of the trees pruned in the winter were attacked by DFPM than would be expected. Five percent of the trees pruned in autumn were attacked by DFPM. One percent of the trees pruned in winter were attacked by DFPM. Thirteen percent of the trees pruned in the spring were attacked by DFPM. Two percent of the trees pruned during the summer were attacked by DFPM.

Table 5. Number of ovipositions by DFPM associated with pruning wounds on trees with branches pruned through the branch collar and trees with branches pruned outside the branch collar.

TREATMENT	NUMBER OF OVIPOSITIONS BY DFPM	CHI-SQUARE STATISTIC	P VALUE
PRUNED THROUGH BRANCH COLLAR	291	$\chi^2_c = 129.365^{**}$	$P < 0.001$
PRUNED OUTSIDE BRANCH COLLAR	73		

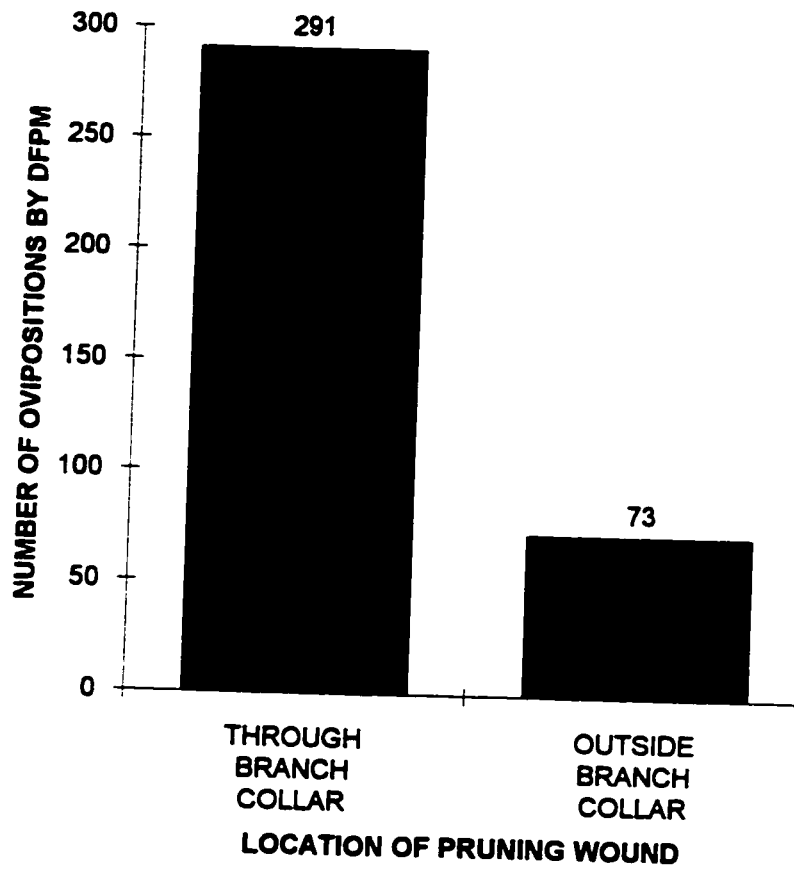


Figure 10. Number of DFPM ovipositions at pruning wounds made through the branch collar and at pruning wounds made outside the branch collar.

Table 6. Number of trees pruned in autumn, 1995; winter, 1995-1996; spring, 1996; or summer, 1996 on which DFPM oviposited.

TIME OF PRUNING	NUMBER OF TREES ON WHICH DFPM OVIPOSITED	NUMBER OF TREES ON WHICH DFPM DID NOT OVIPOSIT	CHI-SQUARE STATISTIC	P VALUE
AUTUMN	5	95	$\chi^2_3 = 17.841^{**}$	P < .001
WINTER	1	99		
SPRING	13	87		
SUMMER	2	98		

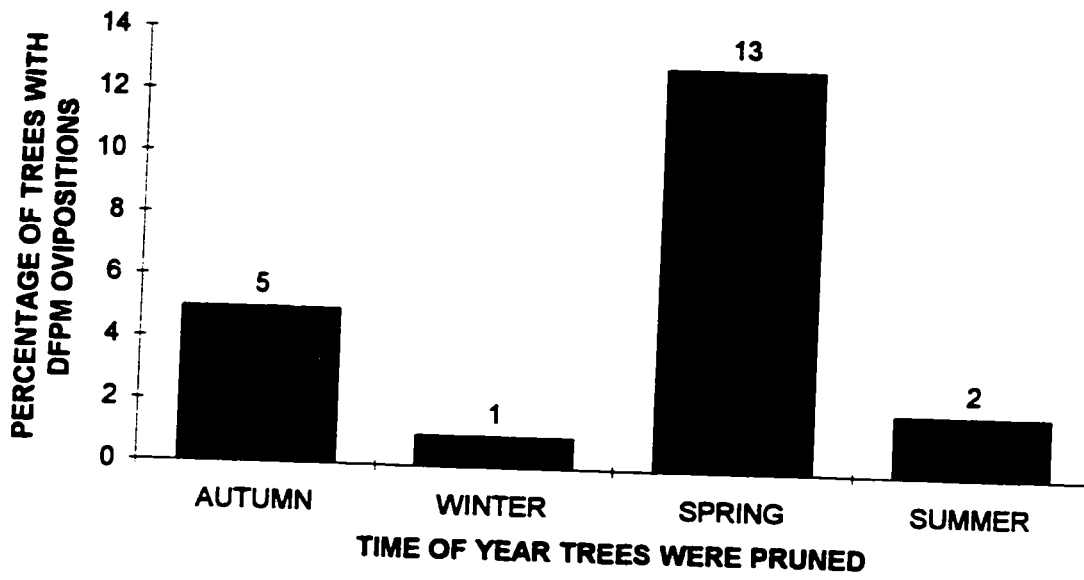


Figure 11. Percentage of trees pruned in autumn, winter, spring, and summer with DFPM ovipositions.

DISCUSSION

About 20 percent of the trees pruned at the Cumberland site in 1991 were attacked by DFPM in the 4 years following treatment. Several of these trees were attacked numerous times. These observations suggested that DFPM may find certain trees to be more attractive than others. In fact, a significantly greater number of the trees attacked by DFPM following the 1991 pruning lift were attacked once again by DFPM compared to trees pruned in 1991 but not attacked by DFPM, after both groups were given a second pruning lift in 1995.

The ability of the DFPM to discriminate between potential hosts together with its propensity to oviposit on specific individuals within the population is further supported by their preference for certain clones. A preliminary survey of DFPM attacks on trees in the Longview block of the Rochester seed orchard revealed a wide range in average number of DFPM attacks per clone. Formation of meaningful conclusions regarding the relative attractiveness of the clones to DFPM, however, was frustrated for various reasons. For example, the number of stimulation wounds sustained by individual trees varied considerably. Moreover, the combination of clones that received stimulation wounds varied from year to year as did the numbers of trees within clones. However, the ability of the DFPM to differentiate between clones is clearly illustrated by the significant difference in number of DFPM attacks at stimulation wounds made in 1996 on each of 5 trees representing 6 of the clones that were wounded.

Clearly the DFPM selects its hosts in response to olfactory cues. The DFPM oviposited only when trees were wounded and exuded oleoresin. It is unlikely that the quantity of oleoresin is important to the attractiveness of a particular host. All of the trees at the Cumberland site that were treated had similar quantities of exuded resin but not all trees were attacked. Further, some trees with wounds that produced copious amounts of resin were not attacked. Rather, the DFPM most likely selects hosts for oviposition in response to the volatile constituents present in the oleoresin as well as the proportions of these materials.

Monoterpene composition has been found to vary between tissues, within trees (Zavarin 1968, Roberts 1969) and may also explain the preference of DFPM for wounds made to the bole of trees over branch wounds. Resin is produced by tissues occluding wounds and from preformed resin canals (Shigo 1989). Differences in quality between resin produced as a wound response and resin that was formed prior to the wounding may be significant. Further, compared to branch wounds, wounds to the bole of a host tree may sever more preformed resin canals. Thus, variation between bole and branch wounds in the ratio of preformed resin to resin formed at wounding may explain DFPM preference for bole wounds.

In order to demonstrate the preference by DFPM between wounds made to the bole of trees and branch wounds, an equal number of wounds were made to each tree. It was felt that removing the branches from trees to one half total tree height while

wounding the bole of other trees a like number of times would alter the host odor plume between treatments adversely. Variation in tree heights would also require pairing trees of equal size to ensure that smaller trees would not receive a disproportionate number of bole wounds compared to the number of branch wounds on larger trees. Accordingly, 8 branches were removed or 8 wounds were made to the bole of the treated trees. One of the consequences of this strategy was that less attractive host odor was produced than would be expected from an operational pruning. Fewer attacks by DFPM might be expected under these conditions.

Another consequence of this approach was maintenance of live branches in close proximity to branch and bole wounds. While oleoresin is produced at the wound site from epithelial cells surrounding resin canals and from tissue occluding the wound, photosynthate required by cells to produce oleoresin originates in the foliage. In operational pruning, total foliar surface area is significantly reduced, limiting the amount of photosynthate available for resin production while creating significantly more sinks, i.e., wounds, for photosynthate allocation. Moreover, a longer period of time would be required for photosynthate to reach wounds further from the base of the live crown than wounds closer to the live crown. Maintenance of relatively full crowns in this study may have also interfered with DFPM flight and dispersal of host odor plumes. Therefore, my results may be more conservative than expected under operational conditions and may explain the low number of captures.

Variation in resin quality may also explain DFPM preference for branch wounds made through the branch collar over branch wounds made outside the branch collar. In conifers, that portion of a branch that lies within the bole of a tree and extends into the branch collar is impregnated with resin. High concentration of resin in this portion of a branch forms a protection zone that serves as a barrier to the spread of fungal pathogens. Cutting through the branch collar compromises the branch protection zone. Pruning outside the branch collar maintains the branch protection zone intact. The difference in host odor between these type of wounds may be significant.

One method of pruning stipulates that the cut must be made outside the branch collar. Cuts made outside the branch collar maintain the branch protection zone, a barrier to the spread of fungal pathogens causing wood rot. Another approach to pruning advocates making the cut through the branch collar. Proponents of the latter approach maintain that wound occlusion proceeds more quickly when the cut is made through the branch collar than when the cut is made outside the branch collar.

Initial entry into stands targeted for commercial pruning typically occurs when trees are 10.2 cm (4 in) to 15.2 cm (6 in) dbh. Wood rot caused by fungal pathogens would be limited to a small diameter defective core where pruning compromises the branch protection zone. The loss in revenues that would result from decay of the small knotty core would be more than compensated for by the increased value of

clear wood produced over a minimum 55-60 year rotation. Pruning through the branch collar also reduces the branch stub length and promotes more rapid production of clear wood as well as greater volume of clear wood.

Pruning through the branch collar in commercial operations is a strategy that is highly attractive, for the reasons stated above. However, a significantly greater number of trees are attacked by DFPM when pruned through the branch collar than outside the branch collar. Further, total number of attacks by DFPM are significantly greater among trees pruned through the branch collar than outside the branch collar. Therefore, pruning through the branch collar is likely to extend the diameter of the defect core and actually reduce the amount of clear wood produced following treatment by encouraging damage from DFPM.

Timing of pruning activities may directly affect resin quality and therefore host preference by the DFPM. Douglas-fir trees pruned in 1991 at Pack Forest and at the Cumberland site were attacked by DFPM for years following treatment (Johnson 1993). The number of attacks by DFPM actually increased in the second year. Attacks by DFPM continued in the third and fourth years following treatment and ceased with wound occlusion (personal observation). For this reason, pruning activities conducted at a particular time of year was not viewed as a viable strategy to prevent attacks by DFPM likely to occur in subsequent years. However, pruning at Pack Forest and at the Cumberland site in 1991 was carried out between May and

September and not at other times of the year. The subsequent finding that a significantly greater number of trees pruned in the spring were attacked by DFPM than at other seasons of the year demonstrates that timing of pruning activities can be an effective strategy for reducing damage by DFPM. The low number of attacks by DFPM on trees pruned in the winter is most probably due to little or no resin being exuded at that time. Wounds made in autumn did exude resin but the quality of that resin would likely differ from resin exuded from wounds made in the spring because more time had elapsed since pruning which would allow for greater loss of the more highly volatile constituents of the resin. Resin quality of summer pruned trees would likely have a higher proportion of highly volatile constituents than trees pruned in either fall or spring. Consequently, both the volatile constituents as well as the relative proportions of resin volatiles perceived by the DFPM varies with the amount of time that has elapsed since pruning.

Implications for Intensive Management

Pruning and thinning forest stands has been proposed as a means to create old growth structures that would benefit plants and animals dependent on habitat with these type of structures and to promote biodiversity within a landscape (Oliver 1992). These activities would also provide jobs improving the economic health and stability of rural communities, improve wood quality, increase revenues, and improve the ability of stands to resist injury from secondary insects. However, pruned stands of

Douglas-fir are both susceptible and vulnerable to attacks by DFPM, a primary insect.

Increases in the number of attacks together with increase in multiple attacks are likely in pruned Douglas-fir stands. This eventuality could decrease stand vigor and make individual trees susceptible to attacks by secondary insects, *e.g.*, the Douglas-fir bark beetle, *Dendroctonus pseudotsugae*. Moreover, DFPM scores the sapwood of its hosts and renders trees significantly more prone to wind breakage. At the very least, continued attacks will reduce the production of clear straight grained wood along with anticipated revenues. Revenue projections must account for losses due to activity of DFPM. This is particularly true for pruning operations conducted later in the rotation of a stand where revenues are marginal.

A number of strategies can be employed to reduce the impact of DFPM in pruned stands of Douglas-fir. Remedial control measures would be warranted if increases in DFPM populations threaten the survival of a significant number of individuals in the stand or damage is expected to exceed a predetermined injury or economic threshold. However, the results of this research suggest specific preventive measures that may make costly remedial efforts unnecessary. One strategy that may prove valuable would be to use genetic material which exhibits low susceptibility to attack by DFPM as planting stock in the establishment of forest plantations expected to be pruned at a later date. Alternately, trees shown to be highly susceptible to attack by

DFPM could be planted along with less susceptible genetic material. When pruning operations were conducted, highly susceptible trees would function as trap trees. Trap trees would be removed in a subsequent thinning operation following occlusion of pruning wounds on leave trees.

Pruning should be carried out as early in the rotation as possible. Damage by DFPM early in the rotation will be restricted to a small defective core. Pruning branches when they are small in diameter will also favor rapid occlusion of wounds and reduce the time these wounds are susceptible to DFPM attack.

Pruning should be executed with care. Since wounds other than branch wounds are also attractive to the DFPM, an effort must be made not to inadvertently scar the bole of the tree. Care must also be exercised to make sure pruning wounds are made outside the branch collar not through the branch collar.

Finally, damage from DFPM may be reduced if pruning is prohibited in the spring. Pruning would be permitted once the DFPM flight period has ended. Monitoring the DFPM flight period could be accomplished using sticky bottom wing traps baited with the sex lure (Z,Z)-3,13-octadecadien-1-ol-acetate that mimics the DFPM sex pheromone. Alternately, where excessive cambial dieback is also of concern, pruning could be delayed until the dormant season in which case use of sex lure traps would be unnecessary.

Mass trapping with pheromone traps may prove valuable as a component of treatment to reduce damage from DFPM in special cases, i.e. Douglas-fir seed orchards. However, pheromone traps are of limited value. While mating may be significantly reduced or even potentially eliminated at the site, females that have successfully mated outside the pruning unit would be attracted to the host odors and still oviposit.

Directions for Further Research

Some Douglas-fir are less attractive to the DFPM than others. However, it is also true that Douglas-fir of relatively low susceptibility are still more susceptible to attack by DFPM than unwounded hosts. Therefore, the efficacy of using only genetic material for plantation establishment which exhibits low susceptibility to DFPM attack in the absence of highly susceptible material needs further investigation to determine if attacks by DFPM would actually be reduced.

Further research is also needed to determine the relative attractiveness of Douglas-fir clones used for plantation establishment. The observational study conducted at the Rochester seed orchard comparing 6 of the clones pruned in 1996 points to the need for designed field experiments comparing limited numbers of clones. In addition, research should be conducted to assess the relative attractiveness of Douglas-fir compared to other species such as lodgepole pine. If lodgepole pine is more

attractive to the DFPM than Douglas-fir, then lodgepole pine could be used for trap trees. The advantage of using lodgepole pine as trap trees is that they would be more easily identified than Douglas-fir used for trap trees when the time to prune is at hand.

Field studies in turn should be followed or combined with analysis of oleoresin quality using gas chromatography. Linking electroantennogram (EAG) trials with gas chromatography would help determine which constituents or combination of constituents in which specific proportions are particularly attractive to the DFPM. These laboratory procedures would also be useful to discern the difference in resin quality between wounds made outside the branch collar compared to through the branch collar and to discern the difference in resin quality between wounds made at different times of the year. If the highly attractive components of the resin are identified along with the optimal proportions of those constituents, lures to attract ovipositing females could be used in sticky bottom wing traps to reduce attacks as an alternative to using trap trees.

Conclusions

- 1) DFPM host preference varies significantly between individual Douglas-fir trees within the general population of hosts.
- 2) DFPM host preference varies significantly between clones of Douglas-fir.

- 3) DFPM oviposits at wounds made to the bole of a host more often than at wounds made outside the branch collar.
- 4) DFPM oviposits significantly more often at pruning wounds made through the branch collar than at pruning wounds made outside the branch collar.
- 5) DFPM oviposits significantly more often at pruning wounds made in the spring than at pruning wounds made in the summer, autumn, or winter.

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PUBLICATIONS

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SEMINARS, LECTURES, AND OTHER EDUCATIONAL PRESENTATIONS

Integrated Pest Management Strategies for Leafminers, a Presentation for the Green Gardening Program: Successful Integrated Pest Management (IPM) Strategies for Professional Groundskeepers, November 14, 1996, Center for Urban Horticulture, University of Washington

Current Research on the Douglas-fir Pitch Moth, a Presentation to Mr. Zhou Jiansheng, Director of Anhui Forest Biocontrol Center, and Mr. Shi Jin, Chief of Protection Division, Anhui Province, Peoples Republic of China, November 13, 1996, College of Forest Resources, University of Washington

Thresholds: When do we spray?, a Pesticide Recertification Seminar for Seattle Parks Department, November 1, 1996, Woodland Park Zoo, Seattle, Washington

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Comparison of Integrated Pest Management Strategies for Insects, Pathogens, and Competing Weed Species Within the Ornamental Landscape, a Lecture for the Pesticide Laws and Safety Class, February 7, 1996, Edmonds Community College, Edmonds, Washington

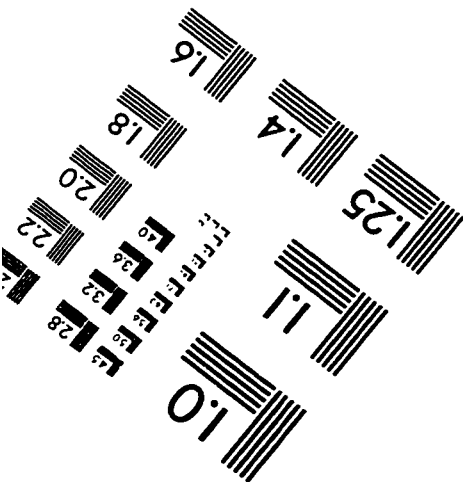
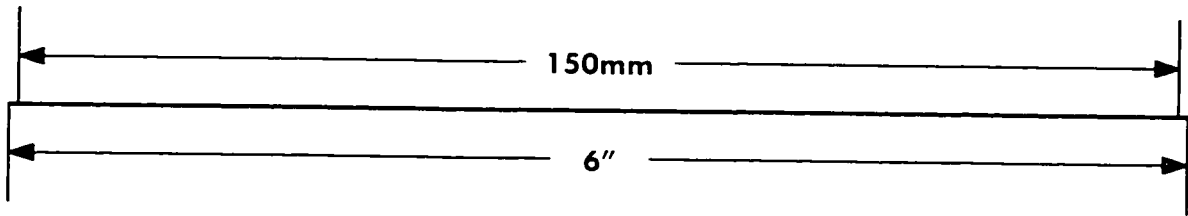
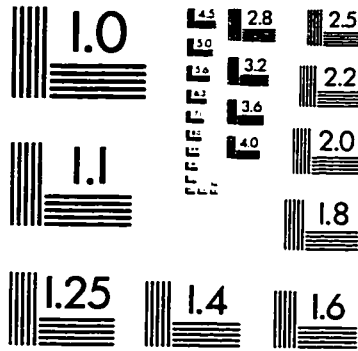
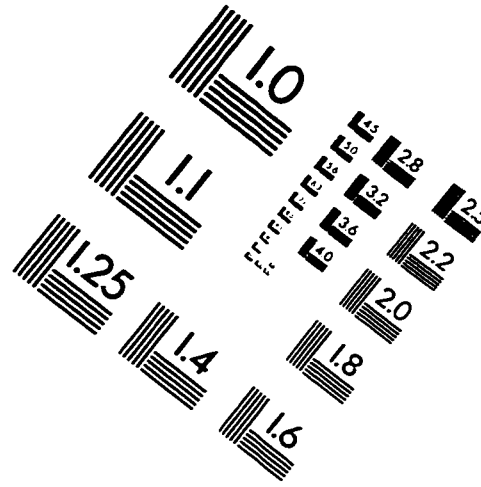
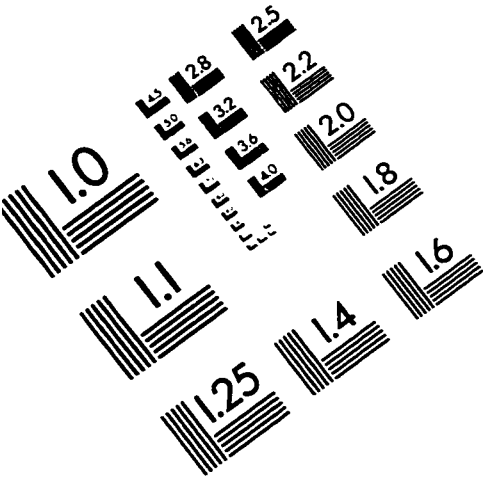
An Integrated Pest Management Approach for the Control of the Elm Leaf Beetle, *Pyrrhalta luteola* (Muller) (Coleoptera:Chrsomelidae), a Presentation at the Meeting of the Washington State Entomological Society. September 30 and October 1, 1994. Center of Urban Horticulture, University of Washington.

Integrated Pest Management of Ornamentals, A Presentation at the 47th Northwest Turfgrass Conference. October 11-13, 1993 Yakima, Washington.

Reducing Pesticide use by employing an Integrated Pest Management Approach with Special Emphasis on Elm Leaf Beetle, a Presentation for the Seminar: Using Alternative Methods and Materials, August 17, 1993 at the Center for Urban Horticulture, University of Washington

Bugs and Crud, A Presentation at the Meeting of the International Society of Arboriculture. July, 1993, Tumwater, Washington.

IMAGE EVALUATION TEST TARGET (QA-3)



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