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INFLUENCE OF SITE AND OTHER FACTORS ON DAMAGE BY THE EUROPEAN PINE SHOOT MOTH

by

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of the requirements for the degree of
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CHAPTER I

INTRODUCTION

Since the introduction of the European pine shoot moth, (Rhyacionia buoliana [Schiff.]), in the early part of this century, the most seriously damaged host has been red pine (Pinus resinosa Ait.). Although entire plantations have been ruined, variations in the amount of injury to the trees have been observed. Past studies have attributed these variations to the insect. This study explores the possibility that differences in the amount of damage may be attributable to the tree.

A review of the literature reveals that American forest entomologists have not studied the effect the host tree may have on the insect. The assumption has been made that, once infested, any stand will suffer severely. However, in the native range of the insect, severe damage to Scots pine has been correlated with low site quality by some European forest entomologists.

In this study preliminary comparisons indicated that variations in the amount of damage seemed to be related to site quality. The dating of old attacks by the shoot moth made possible the simultaneous comparison of injury within and between stands, the evaluation of the causes of variations, and the recognition of dominant control factors. The correlation between injury to trees and various site factors has been tested through multiple regression analysis of data collected in two counties in Michigan infested with the shoot moth. The criteria

for selection of study areas and plots, techniques used in measuring the trees, the effects of the insect, and the site conditions are described. Soil moisture deficits proved to be the most important site condition associated with severe injury to red pine by the shoot moth.

CHAPTER II

LITERATURE REVIEW

Previous American Research

American forest entomologists have not studied the possibility that an association may exist between site quality for red pine and the intensity of tree injury by the shoot moth. However, the possibility that site quality may have an affect on tree resistance is suggested by variations in shoot moth damage reported in Connecticut by Friend and West (1933) and in Michigan by Rudolph (1949). They attributed differences in injury to the slow dispersal of the moths, rather than to any condition of the site for red pine. Friend's and West's comments were:

> "Quality of site as reflected in the growth and general vigor of the trees has little effect on their susceptibility to attack. . . . In one instance a plot on a poor site was so badly infested that the stand was cut and burned. Infestations fully as severe occur on the better sites. As is to be expected, the slow-growing stands succumb more rapidly to the attack of the insect. Although European observers are of the opinion that the trees on poor sites are more readily infested, this has not been observed to be the case here. Munroe (1920) [sic] suggests that a severe attack may be an indication of a poor site, but observations made on Scotch pine in Europe cannot always be used as a basis for judging the susceptibility of red pine in America. At present there is little information available regarding infestations in stands on poor sites in this country.
>
> "The time for a heavy outbreak to develop on red pine good sites usually requires three years from the time of introduction, and by the fifth year it may become extreme, destroying the stand as an economic unit."

Admittedly, this is a brief review of the American literature pertaining to the influence of site quality upon the resistance of red pine to attack by the shoot moth; but there have been no previous studies on this subject.

European Studies

The status of European research prior to 1930 has been adequately reviewed by Friend and West (1933). They summarized the only European references pertaining to site quality as follows:

> ". . . Taschenberg (1880) considered the insect to be especially injurious to young pines from ten to fourteen years old growing on light soil, but not very serious in older stands. He was of the opinion that once the insect became established in a plantation it persisted as an injurious pest until overcome by parasitic enemies or until the trees became tall. Judeich and Nitsche (1895) mentioned several outbreaks that occurred in the first half of the nineteenth century in central Europe and expressed the belief that the greatest damage occurred on pines from six to twelve years old growing on poor soil, and that stands more than thirty years old were no longer subject to injury. They distinctly state, however, that vigorous trees may be attacked. . . . Escherich (1931) discusses the insect at some length and expresses the opinion, prevalent among European entomologists, that slow-growing stands on inferior soil, which are open and exposed to the sun, suffer most, although vigorous stands on good sites sometimes are severely attacked."

During the 1930's, Butovitsch (1936) in Sweden pointed out that heavy shoot moth attacks occurred on the better morainic soils as well as on the poor wind-blown sandy soils. He attributed variations in insect damage to stand closure. Butovitsch's opinions on the importance of site quality were brought to the United States by Parr (1937) who stated:

> "It was apparent from the data obtained from the sample plots investigated in Blekinge (Sweden) that the site quality did not materially affect the infestations. Trees on the better sites were as susceptible to attack as those on the poorer. The trees on the poorer sites, however, may be more seriously injured than those on the good sites because they are generally smaller and more slowly growing, requiring longer for the plantation to close."

In England, Munro (1919) warned that shoot moth damage was an indication of poor soil. But Ryle (1928), after studying a shoot moth

attack at East Anglia, believed that:

> ". . . There appears to be no evidence or even probability that Retinia (Rhyacionia) is more prominent on sickly trees than in healthy plantations, and pines grown under the most ideal conditions would be just as liable to become infested as those grown under inferior conditions. . . . liable to get more help from a study of the biology of the insect than from an ecological study of the host tree."

During the next shoot moth outbreak in East Anglia, Brooks and Brown (1936) suggested that insect damage is:

> ". . . retarded or accelerated by the state of health of the trees. This is directly dependent upon the quality of the plants, soil conditions, and climate. As regards climate, extremes (especially hard winter frosts and summer droughts) appear to increase economic damage."

The first study of host-site quality interactions in research on the shoot moth was made in Belgium by Voûte and Walenkamp (1946). They showed a direct association of past outbreaks with dry Julys during the period 1893-1940. Their findings were supported by Neugebauer (1952) in Germany. Voûte and Walenkamp believe that low resistance of the tree to the shoot moth is the result of an unfavorable moisture situation. They observed damage to Scots pine to be associated with very dry sites, deeply tilled sites, or sites with a high water table.

Thus we see that--although the possible influence of site quality upon a shoot moth infestation has been recognized by European entomologists--no specific studies have been undertaken. In Europe, Canada, and the United States, studies of the shoot moth have concentrated on the biology of the insect.

CHAPTER III

DEVELOPMENT OF THE SITE QUALITY HYPOTHESIS

Identifying and Dating Shoot Moth Attacks

Red pine buds that are damaged by the shoot moth often remain on the tree for as long as nine years (Fig. 1). The destroyed bud can be dated because of the uninodal growth characteristic of red pine; thus it is possible to determine the year of initial attack by searching for the oldest damaged bud (Figs. 2 and 6). Once the length of an infestation is determined, infested plantations in widely separated areas can be compared. The identifying and dating of past shoot moth attacks is based upon a knowledge of the insect's biology, the appearance of current and past injury to the tree, and the ability to distinguish damage by other causes (Heikkenen, U1958a, 1960).[1] These requirements are discussed in the following sections.

Insect biology

The needles, buds, and shoots of the host tree provide the insect with food and shelter during the larval and pupal stages. After the needle-mining period, the early instar larva mines a newly formed bud beginning in late June and early July. This injury is termed, in this dissertation, summer injury. After over-wintering in the bud, the late

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[1]The "U" in the citations refers to unpublished manuscripts. These are listed in the Literature Cited: Unpublished.

instar larva usually becomes active about the middle of April. Spring injury occurs when the larva bores into fresh buds or, infrequently, into the elongating shoot. The insect pupates within the bud or shoot and the adult emerges after two or three weeks. The flight period lasts for about one month, beginning in mid-June. One generation a year occurs in North America. The most recent accounts of shoot moth biology are to be found in publications by Pointing (1961, U1963), Green (1962a), and Green and Pointing (1962). These contain bibliographic references to earlier work.

Description of injury

Infested red pine buds can be detected by resin exudates, frass accumulations, entrance and emergence holes, and empty pupal skins. Shoot moth attack during past seasons can be identified by mined buds, reduction in the number of branches per whorl, and stem deformities such as crooks, forks, posthorns, bushy tops, and spike tops. Tree injury as old as thirty-four years has been identified by one or more of these characteristics (Fig. 3).

The damage to the tree's form or growth varies with the position of the attacked bud on the tree or within the bud cluster, the time of year the bud or shoot was attacked, the extent of the insect's feeding, and the subsequent development of the bud or shoot. The following types of stem injuries are characteristic of shoot moth attack.

Pruning.--The lateral buds in the terminal bud cluster may be destroyed either in the summer or in the spring. The result is, in effect, a pruning of side branches. This reduction of branches in the whorl may be complete or, in the case of light injury, only one may be lost. If all lateral buds are killed, the bud scale scars will remain

as evidence of the internode until bark sloughing occurs. The loss of the lateral buds produces no crook in the main stem (Fig. 1).

Crook and fork.--In some instances the terminal buds are destroyed. If undamaged lateral buds are present, a lateral shoot usually assumes the lead and continues height growth. The result may be a crook in the main stem. The loss of form will depend on the degree of offset and the number of lateral shoots that continue height growth. When two or more laterals assume dominance, a forked stem is the result. Many variations of crooking and forking can occur (Fig. 3).

Posthorn, bush and spike.--During the spring, late instar larvae occasionally feed upon the side of the developing terminal bud or shoot. If feeding stops before the shoot is killed, the injured leader often bends at the point of attack. If the injured shoot continues to grow, a characteristic "posthorn" is formed (Fig. 4).

When all buds on the terminal shoot are destroyed, adventitious buds may form. If these buds are destroyed, additional adventitious buds may form. The resulting shoot growth resembles a "bush". A lateral below the "bush" usually assumes dominance (Fig. 5). This type of damage is perhaps the most reliable indicator of past attacks by the shoot moth.

When adventitious buds do not develop and the insect attack kills the terminal, the dead top is referred to as a "spike".

Injury by other causes

Not all of the stem deformities in red pine are caused by the shoot moth. Similar injury may be inflicted by other insects, mammals, birds, disease, weather, or man. However, these injuries are usually distinguishable.

Damage by the Saratoga spittlebug (Aphrophora saratogensis [Fitch]), the white pine weevil (Pissodes strobi [Peck]), and a pine tip moth (Rhyacionia adana Heinrich) resembles tree injury by the shoot moth. Spittlebug injury can be differentiated by necrotic spots in the phloem of the branches or flagged branches resulting from nymphal feeding punctures. Weeviling can be detected by the adult emergence holes. Injury by the pine tip moth is confined to trees less than three feet in height. Cocoons may be found in pitch masses in the soil near the trunk (Martin, 1960).

Tree injury caused by other insects is occasionally encountered. Lyons (1956) has reported that the red pine cone beetle (Conophthorus resinosae Hopk.) may kill the shoots of sapling and pole-sized red pine and over-winter in the vegetative buds. He also states (1957) that some of the native Dioryctria species occur occasionally in red pine plantations and have caused severe damage along the southern edge of the tree's range. The larvae of Dioryctria zimmermani (Grote) have been found feeding in the pith of the current year's shoots of red pine (Lyons, 1957, and Rennels, 1960).

Insects which occasionally bore into the buds and pith of red pine are the Nantucket pine moth (Rhyacionia frustrana [Comstock]) and the pitch pine tip moth (R. rigidana [Fernald]). Miller and Neiswander (1959) report these two insects are more frequent in red pine planted south of the tree's natural range. Although the native Dioryctria and Rhyacionia species may kill the shoots of red pine, adventitious buds seldom develop. I have observed very few cases of pruning, bushy tops, or posthorns, as may be the case, with the shoot moth. Martin (1959) has observed that in Canada the pine bud moth, Exoteleia dodecella L.,

has caused tree injury similar to that of the shoot moth. But the majority of attacks on red pine were limited to the lateral buds and occurred near heavy infestations of Scots and Mugho pine.

Infrequently, localized damage to the main stem or the lateral shoots of red pine is caused by porcupines, rabbits, red squirrels, and the pine and evening grosbeaks. The probability of confusion with attack by the shoot moth is slight. The shoot moth does not remove the bark or clip off the buds and shoots.

The only disease reported to kill the current season shoot growth is caused by Diplodia pinea (desm.) Kickx. Although recent damage by this fungus may resemble that of the shoot moth, close observation reveals the presence of mycelia and fruiting bodies. The disease, according to Waterman (1953), stunts tree growth and may eventually kill young trees. The fungus, Dematium pullulans de Barry (=? Pullularia pullulans [d By.] Berkhout.) has been associated with the forking of red pine in New York by Jump (1928).

Red pine shoots can be damaged by various weather conditions.[2] Hail damage, according to Benjamin (1957), is distributed evenly throughout a given area with bark lesions restricted to the windward side. Often summer frost will quickly kill the foliage in terrain depressions (Pomerleau and Ray, 1957). Buds do not exhibit shoot moth attack unless the stand was infested prior to death. Carvell (1956) believes red pine forking to be associated with early summer droughts followed by late summer rains, and Littlefield (1956) thinks it may be correlated with early summer droughts and low site quality. Forking has also been reported in

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[2]Personal communication: Succulent terminal shoots can often be whipped out of the tree by high winds during early June, according to Zahner (1963).

Wisconsin by McCabe and Labisky (1959).

Heavy wet snows in young plantations may often tear out lateral branches or bend the stem (Guilkey, 1958). Branch breakage usually occurs below the top two whorls. Presence of the dead branch usually identifies this type of injury.

In 1961 Miller and Schullau (U1963) discovered shoot moth-like damage in Minnesota where the insect has not been reported. What factors caused the apparently identical damage were not discovered.

Dating attacks

After identifying an attack by the shoot moth, the injury to the tree can be quantified by establishing the time when the attack occurred and measuring how much the tree was affected.

Damage to the main stem in the form of pruning, crooks, and forking can be dated by the number of years represented by the internodes between the terminal and the point of injury (Fig. 6). Damage in the form of posthorns, bushes, and spike tops can be dated by counting the internodes on a relatively undamaged lateral branch below the point of injury. Care should be taken to avoid counting false internodes created by "summer shoots". When all branches are badly damaged, a specific injury can be dated by counting the annual rings just below the point of injury. The presence of a bush or spike infrequently indicates the loss of a year's height growth. The years lost can be determined from the age of the stem below and above the point of damage.

Variations In Tree Injury

During the spring of 1958, Miller discovered a sharply delineated area of lightly damaged red pine within a severely injured plantation (Fig. 7). The dating of past attacks suggested that all trees had been subject to attack for an equal period of time. Height growth of the severely injured trees appeared to have been stopped in 1958 yet in the lightly damaged trees height growth had continued (Fig. 9). Similar variations in shoot moth injury within plantations were observed during the summer of 1958 in both Michigan and Ontario, Canada (Figs. 8, 10 and 11). In all cases the lightly and severely damaged red pine had been subject to attack by the shoot moth for an equal length of time.

Areas of severely damaged red pine which had been infested annually for more than thirteen years were also found in Michigan. The shoot moth had reduced these trees to bushes (Fig. 12). It is important to note that examination of apparently uninjured plantations near severely damaged trees revealed that the insect was present (Fig. 13). Reductions in the annual number of branches per whorl showed that injury varied during specific years (Fig 14). Although these trees were still infested, normal height growth had continued.

The differences in injury suggested that some sort of natural control was operating. This concept is at variance with previously expressed American opinion, summarized by Miller and Neiswander (1955) as follows:

> "Injurious insects of the forest may be divided into three groups characterized by three different population types: (1) periodically eruptive populations, (2) sporadically eruptive populations, and (3) balanced populations at high density (Graham, 1939). The European pine shoot moth belongs in the last group. This type of behavior means that wherever the insect is present at all, it is currently occurring, or is destined to occur, in large numbers if not controlled by artificial means. Satisfactory natural control within the usual distributional range of the shoot moth is unknown. Also, if an infested stand has been treated mechanically or chemically and a few infested tips escaped the treatment, the population will build up in the same manner as from initial incidence. Friend et al. (1938) noted that the time required for equilibrium (balanced population at high density) to be attained from initial incidence in red pine plantations in Connecticut is from three to five years. Hawley and Lutz (1943) presented additional observations in Connecticut substantiating this factor, and the present writers have found it to apply in Ohio."

In Michigan, plantations were also observed that had recovered from severe damage by the shoot moth. Such an outbreak occurred during 1946-47 in red pine plantations on the Stinchfield Forest of the University of Michigan. More than one hundred live larvae (spring count) were on the average tree (Melton, U1947). Although serious tree damage resulted, the trees resumed normal height growth in 1948 (Fig. 15).

In order to obtain more evidence of tree recovery I visited the oldest infestation in the country. The first outbreak on red pine had occurred in the 1930's on the Eli Whitney Forest of Yale University near New Haven, Connecticut. There the first American studies on the shoot moth were conducted by Friend and West (1933). To assure re-examination of the original plantations, Dr. R.B. Friend identified them for me in the field during October, 1958.[3] The data gathered on these plantations proved invaluable to this study. The trees had recovered (Heikkenen,

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[3]I am especially indebted to Dr. R.B. Friend for his advice and help in the beginning of this study.

U1960); height growth had continued in a normal manner (Figs. 17 and 18).

In the winter of 1958-59 the Ohio plantations where Miller and Neiswander (1955) had studied the shoot moth were re-examined. These trees had also resumed normal height growth (Heikkenen, U1959a). The past damage and subsequent recovery were obvious when the mean annual height growth and the number of branches per whorl were plotted (Figs. 15 and 16). During the outbreak the number of branches per whorl had dropped to less than two during 1952-54. But in 1955-57 there were more than three branches per whorl.

The recovery of some severely damaged plantations was also at variance with previous American opinion on decline of shoot moth populations, summarized by Miller and Neiswander (1955) as follows:

> "It is a well documented fact that entry of the shoot moth into a closed, or an old stand, is not a matter for concern. The pre-closure period is the critical period in the life of the stand as regards damaging population levels. If the shoot moth population can be prevented from building up prior to closure, the insect usually will never cause significant damage but if a moderately dense population is present by the time the trees are six feet high, serious injury may continue for some years after closure; if the population reaches equilibrium before the trees are six feet in height, there is little chance that the stand will recover (Friend et al., 1938; Hawley and Lutz, 1943)."

The plantations which had recovered in Michigan and in Ohio had been heavily infested prior to closure. The Connecticut plantation was heavily infested after the stand had closed.

Causes of Variation in Shoot Moth Attacks

What causes the wide variation in tree injury in plantations infested for equal lengths of time? Two broad possibilities exist: either there is some variation in the oviposition habits of the shoot moth or differences occur in larval mortality.

Oviposition habits

Past studies have attributed variations in attacks by the shoot moth to the behavior of the insect. The moth was believed to be a poor flyer, having a slow rate of spread and a tendency to reinfest the same tree year after year (Friend and West, 1933; Miller and Neiswander, 1955). However, in 1957 evidence began to suggest that the shoot moth was capable of rapid dispersion. Considerable movement was shown by Green et al. (1957) with the use of a radioactive tracer. Green and Pointing (1962) have now proved that the insect has strong flight potentialities.[4] The distribution of past attacks throughout entire plantations supports Green and Pointing's conclusions concerning the dispersal of the shoot moth.

But evidence based on actual egg counts was needed to determine whether or not oviposition varied from location to location within the same plantation. An exploratory study was made after the 1958 moth flight (Heikkenen and Miller, 1960). In Ottawa and in Wexford Counties, Michigan, a severely damaged plantation with "islands" of lightly damaged trees was selected. In adjacent areas of contrasting damage, a shoot

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[4]The advice and interest of the Canadian forest entomologists, Dr. G.W. Green, Dr. P.J. Pointing, and Dr. J.A. Juillet, is sincerely appreciated. During August, 1958, much unpublished information was made available to me which contributed greatly to the results of this study (Heikkenen, U1958b).

from the first whorl was clipped from separate trees (between 10 and 30 per study area) and then examined in the laboratory under magnification (2x). No difference existed in the number of eggs on lightly and severely damaged trees (Fig. 8, Table 1).

An expanded oviposition study was made in 1959 (Heikkenen and Miller, 1960). In three young red pine plantations having "islands" of lightly damaged trees scattered among severely damaged trees, adjacent one-tenth acre plots were laid out. One plot was in the lightly damaged group of trees and the other plot was in the area of heavily damaged trees. Oviposition was compared in terms of the mean number of eggs on the mean tree--the mean tree was derived by counting and averaging the number of branches per whorl on about fifty trees. The actual sampling of the trees on the plot was done by starting at a random point on the plot and removing one branch (corresponding to a branch from a given whorl on the mean tree) from each of a series of successive trees. Thus not more than one branch per whorl came from the same tree. The same procedure was used on the lightly damaged trees. The branches were examined under magnification (2x) in the laboratory. The number of eggs found on both the damaged and lightly damaged trees were more than sufficient to provide high larval populations (Table 2). The results strongly indicate that the variation in injury to the trees was not attributable to differences in the oviposition habits of the shoot moth. In fact, there is a probability that large, lightly damaged trees may be subject to more total oviposition, as they present a larger obstruction to flying moths. The conclusion was drawn that all trees in a plantation are subjected to equal oviposition.

Larval mortality

If differences in tree injury could not be attributed to variation in the oviposition habits of the shoot moth, the other broad possibility of larval mortality had to be investigated. Previous American studies of the shoot moth have stressed three mortality factors: cold weather, parasites, and stand closure. Careful consideration was given to these mortality factors in relation to observed variations in tree injury.

Cold weather.--Lethal cold temperatures have been considered the primary cause of shoot moth mortality since West (1936) found that -18° F. killed the over-wintering larvae. The frequency of occurrence of this temperature was used by Rudolph (1949) to predict the locale of damaging outbreaks in Michigan. But severe tree damage has been reported from areas where lethal cold temperatures occur almost every year (Batzer and Benjamin, 1954; Beckwith, 1957). In Wexford County, Michigan, where lethal cold temperatures occur frequently, I also have observed adjacent areas of lightly and severely damaged trees (Fig. 10).

The explanation for severe damage in areas where lethal cold temperatures frequently occur has been found by Green (1962b) to be due to the insulating effect of snow. Green believes that:

> ". . . the European pine shoot moth could exist with little mortality due to freezing almost anywhere throughout the North American distribution of red pine providing that snow cover during the winter months is sufficient to cover infested buds to a depth of eight inches."

The over-wintering survivors are the source of future generations. They have a strong tendency to move up the tree and continue the attack (Green, 1962b). However, the possibility exists that if lethal temperatures occurred in areas of little or no snow cover, a shoot moth popula-

tion could be destroyed. This is believed to have happened to the shoot moth outbreak on the Stinchfield Forest of the University of Michigan in the winter of 1947-48 (Williams, U1957).

The probability exists that lethal cold temperatures are not the primary cause of variations in adjacent areas of tree damage caused by the shoot moth.

Warm weather.--After studying the Connecticut plantations, it was apparent that in addition to the severe outbreak of the early 1930's, there were minor outbreaks in 1935-36, 1943-45, 1949-50, and 1955-57. These years were associated with hot, dry summers. The idea developed that summer weather conditions may influence the shoot moth (Heikkenen, U1960). A study of weather data revealed below normal summer precipit - tion and above normal summer temperatures had occurred during the Ohio outbreak of the early 1950's and the Michigan outbreak of the mid-1950's (Talerico and Heikkenen, U1960a). This information suggested that hot, dry summer weather may be associated with annual variations in outbreaks of the shoot moth.

Other insects.--During the shoot moth outbreaks observed, parasites did not exercise an effective control of the population. The average rate of parasitism is seldom more than ten percent of the host population. The maximum spring parasitism percentages are quite low. In Ohio, Miller and Neiswander (1955) reported seventeen percent, and in Quebec, Béique (1960) found sixty-six percent. It is probable that the sharply delineated areas of lightly injured trees would be searched by the native and introduced parasites. Also there are no reports of sharp delineation in the distribution of shoot moth parasites. Regarding predation, Juillet (1961) has found that spiders and ants may be a larger

mortality factor than most parasites.

In this study the probability is considered quite low that other insects are the direct cause of adjacent variations in tree damage by the shoot moth.

Tree and stand conditions.--The chances are remote that individual tree differences are the cause of variation in tree injury by the shoot moth. Red pine is well recognized as a uniform phenotype. Genotypic differences are usually of a regional nature. Genotypic resistance in plantations infested by the shoot moth would most likely occur in isolated, individual trees. This has not been the case. Variation in the tree damage observed to date has been associated with groups of trees.

The influence of stand closure is debatable. Contrary to past opinion, the entry of the shoot moth into a closed stand can be a matter for concern. Serious damage has been observed in closed plantations in Michigan; some were infested prior to closure, others were infested after closure. Crown closure must also have occurred in one of the infested plantations studied at Rose Pond by Friend and West (1933, Plates VI, VII). These trees had been planted at a six by six foot spacing and when first infested had reached a height of seventeen feet.

The origin of the stand is not important. Although natural seedlings are infested by the shoot moth, the majority of injury to the tree is found in plantations. There are few natural red pine stands remaining within the range of the shoot moth in the United States.

The probability is believed to be quite small that the extent of crown closure, individual tree differences, or the origin of the stand are the primary causes of variation in tree damage on adjacent areas.

Site quality.--The problem still remained to explain why, in spite of uniform oviposition by the shoot moth, some groups of red pine were seriously damaged while others were not. After rejecting the mortality factors previously believed important, the only remaining component of the insect's environment which had not been considered was the condition of the trees themselves.

Observations of tree damage by the shoot moth during the 1958 field season suggested that the severity of tree injury was usually associated with the rate of growth of the tree. Therefore, measurements of tree growth in adjacent areas of lightly and severely damaged trees were taken in the spring of 1958 in Ottawa County, Michigan (Fig. 9). The lightly damaged trees had a much greater rate of height growth than the adjacent severely damaged trees both before and during the outbreak of the shoot moth. The sharply delineated areas of slightly injured trees were associated with a geologic feature--a small dune ridge (Fig. 7). Behind the ridge, on soils with impeded drainage, the trees were severely damaged. This plantation was not an isolated case. Rapid height growth and reduced tree damage by the shoot moth has since been observed in many infested plantations in Michigan, Connecticut, and Ontario.

The differences in the rate of growth of the trees express a variation in site quality inasmuch as site index is based on stand age and height. In an even aged red pine plantation, areas having widely different mean heights are "ipso facto" sites of differing quality. This view in shoot moth research was not unanimously accepted when first proposed.

The association of the growth rate of red pine with tree injury caused by the shoot moth coincided with edaphic features usually asso-

ciated with site quality. Areas of slow tree growth and severe tree injury were often severely wind-eroded (Fig. 12), excessively drained (Fig. 10), and often in association with xerophytic hardwoods. In Connecticut, shallow soils over bed rock appeared associated with severe tree damage by the shoot moth. Areas of rapidly growing resistant trees were usually in well-drained depressions (Figs. 10 and 11), the base of slopes (Fig. 13), not eroded, and associated with mesophytic hardwoods. The lightly damaged plantations usually reached breast height within five years of planting (Fig. 14), and then maintained a mean annual height growth of more than fifteen inches (Heikkenen and Miller, 1960). However, it was also noted that trees with rapid growth rates occasionally became extremely susceptible to attack by the shoot moth. These trees were on shallow soils over bed rock or groundwater.

The study of variations in larval mortality in red pine growing on sites of different quality was initiated during the summer of 1958. Miller and I observed considerable mortality of early instar larvae during the needle-mining period in one rapidly growing, lightly damaged red pine plantation. However there was little larval mortality during this period in nearby slowly growing, severely damaged red pine plantations. We postulated that when red pine was growing in good sites, the needles were somehow capable of reducing the population levels of the shoot moth during the needle-mining period of the early instar larvae.

Hypothesis

The study of red pine plantations infested by the shoot moth for several years revealed wide variation in tree injury within and between plantations. In some plantations, severe injury to the tree by the shoot moth continued year after year while other infested stands were only slightly injured. Areas of lightly damaged trees were found which were adjacent to heavily damaged trees. Plantations were also discovered which had recovered from outbreaks of the shoot moth.

What caused these wide variations of tree injury, especially in the adjacent areas of widely differing tree injury? Egg counts showed that oviposition habits were not involved. Observations indicated that soil characteristics, in conjunction with hot, dry summers, were probably associated with the annual variations in shoot moth outbreaks and the differences in tree injury occurring in adjacent areas. Careful consideration was also given to the natural mortality factors previously considered important. However, these factors were not considered to be the direct cause of variations in tree injury in adjacent areas.

The susceptibility of red pine to shoot moth attack was considered to be associated with the internal moisture stress of the tree, resulting from soil water deficiencies during periods of summer drought. Thus the soil water deficit was thought to provide the common denominator for site comparison. Techniques for this basic measurement of site quality have recently been developed by Zahner (1956) who states:

> "The evaluation of water deficiencies has real meaning when applied under specific conditions. Two variables affect deficiencies: soil and weather conditions. The latter changes with time and place; i.e., from year to year and from one geographic location to another. When time and geographic regions are held constant, it is possible to evaluate water deficiencies of various sites within a region. When a site within a region is held constant, comparisons of deficiencies are possible among years, or even among months. Thus, it is possible to evaluate water deficiencies for many combinations or circumstances. . . ."

Differences in tree injury by the shoot moth also vary in time and in place in apparent association with tree growth and soil water deficits. This association was the basis for the hypothesis of this study: the resistance of red pine to attack by the European pine shoot moth is proportionate to site quality as measured by soil water factors.

CHAPTER IV

METHODS

The testing of the hypothesis utilized a wide range of methods, described in the following sections. Field procedure involved selection of the general study areas and individual study plots, measurement of tree growth and insect damage, and the description and identification of soils. The monthly readily available water capacities and the monthly water deficits of each study plot were calculated for each year (1939-1959) of tree growth from weather records. The field work was done during the summer of 1960. The data were analyzed by multiple regression techniques utilizing an IBM 7070.

Study Plots

The areas selected for study in Ottawa and Wexford Counties, Michigan, provide a sampling of red pine within the central and southern portions of its natural range in Michigan. Within these counties there are numerous red pine plantations of varying ages which have been infested by the shoot moth since the early 1940's. The soils are representative of the podzol region of the lower peninsula of Michigan.

Plot selection

The primary concern in the selection of the study plots was to avoid bias regarding the site quality for red pine and the incidence of tree injury by the shoot moth. The plantations sampled were limited to

pure old field, open grown red pine with spacings ranging from six by six to twelve by twelve feet, planted between 1940 and 1951. The minimum plantation width was two hundred feet. The plots were approximately one-tenth acre in size. A total of sixty-five plots were examined.

The range of site quality in each county was sampled by selecting an approximately equal number of plantations from each major geologic feature where red pine had been planted. The major features in Ottawa County are dune and lake sands; in Wexford County they are moraines, till plains, outwash plains, and meltwater channels. The soil series are generally related to these geologic features, reflecting both parent material and drainage (Table 3).

To assure a proportionate sampling of red pine plantations throughout each county, townships having plantations were combined into "units" (Table 4). In these "units", plantations on a given geologic feature were assigned a random number. These random numbers were then arranged in order numerically. The first five plantations per "unit" in each geologic feature meeting plot requirements were sampled. After a general survey to determine the extent of the geologic feature, the study plot was located by pacing a random direction and distance from a landmark (Table 5).

Tree measurements

On each plot ten trees were measured. These trees were selected by taking five alternate trees along a given row from each of two random starting points. The annual periodic height growth (internodal distance) to date of planting was measured to the nearest inch (Table 6). The diameter (outside bark) was measured to the nearest one-tenth inch at breast height and at one foot above the ground (Table 7). Data on root

characteristics were obtained from a soil pit dug beside a selected tree near the plot center. Measurements to the nearest inch were made on the length of the tap root, the mean depth of the majority of roots, and the maximum depth of rooting (Table 8). Soil profile descriptions were also made (see following Soils description).

Tree injury

Annual injury to the tree by the shoot moth was identified and measured to the date of planting on each of the ten selected trees. Shoot moth injury to the lateral buds was evaluated by counting the annual number of branches per whorl (Table 9). Terminal bud injury was recorded at each node in terms of the number of branches in a fork (Table 10), and/or the presence of a crook, posthorn, bush or spike (Table 11). When terminal growth was stopped by a bush or spike, continuation of height growth by a lateral was measured (Table 12).

Tree injury by the shoot moth in a given year reflects the feeding of the larvae in the spring of the current year as well as the feeding during the summer of the previous year. One generation of this insect spans two chronological years. This situation is the same for the tree; buds are formed in the summer and expand the following spring. When a chronological year is given in this study, it includes the summer of the previous year.

Soils description

Within each plot a soil pit was dug either to a minimum depth of six feet or to a shallower water table or to the maximum depth of rooting. From the bottom of the pit a soil auger was sunk an additional five feet wherever possible. Soil profile descriptions were made and

the soil series identified by the Soil Conservation Service soil scientist in each county, according to specifications of the U.S. Department of Agriculture (Soil Survey Staff, 1951).[5] Included were horizon designation, depth, color (Munsell notations), texture, mottling, structure, and reaction of each horizon. In addition, the depth to water table, structural differences, and free water were measured. Also drainage, relief, slope, horizon irregularities, and class of wind erosion were recorded (Table 13).

A sample of the plow zone was taken for nutrient analysis. The sample was composed of ten soil plugs systematically taken over the plots with a King Tube. The pH, organic matter content, and major elements (N,P,K,C, and Mg) were determined by the Soil Science Department, Michigan State University (Shickluna, 1959)(Table 14).

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[5]I appreciate the advice and the identification of the soil series by Dr. R. Zahner, Associate Professor, University of Michigan, and Dr. W. D. Striffler, Lake States Forest Experiment Station, U.S. Forest Service, and Mr. R. Johnson and Mr. H. Weber, soil scientists, Soil Conservation Service.

Soil Water Deficiencies

To determine the summer water deficits for each study plot, the major contributing soil and weather factors must be known. The major soil variable is the available water storage capacity within the root zone. The precipitation and potential evapo-transpiration are the atmospheric variables. It is then possible to calculate for each plot the water deficit based on water supplied from the soil to meet the potential evapo-transpiration. The procedures for determining these factors are as follows:

Storage capacity

The storage capacity of the root zone was determined for each study plot. The root zone was considered to be the maximum depth from the surface that any root developed (Table 8). These data were obtained from the soil pits.

The storage capacity of the root zone in this study is expressed in inches of water. The technique for determining the available water is described by Franzmeier et al. (1961) as follows:[6]

> " . . . readily available water capacity of soils is a more meaningful expression of the water actually available for plant growth than is the available water content as it is commonly defined. Readily available water capacity (RAWC) is here defined as the difference between the water content of the soil at field capacity and the lower turgor pressure percentage or the difference in weight percentage between the water content of an undisturbed soil sample at 0.06 atmospheres tension and that of a disturbed sample at 6 atmospheres tension."

Available water in volume of equivalent rainfall was computed by multiplying the weight of soil per unit volume of soil by the weight per-

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[6]I am indebted to Dr. E.P. Whiteside, Soil Science Department, Michigan State University, for the use of his unpublished data, and his assistance regarding the soils aspect of this study.

cent of readily available water; the resulting product was then multiplied by the depth of the corresponding horizon (in inches) to obtain the available water in inches. Because horizons vary in thickness, the data were then converted to the available water in inches per foot of horizon (Table 15). On each study plot the storage capacity of the root zone was determined by adjusting the actual depth of each horizon by the inches of available water per foot of horizon for the soil series on which the plot occurred (Table 16).

Precipitation and temperature

The mean monthly precipitation (expressed in inches) for each county during the period 1939-59 was derived by averaging the precipitation records of five surrounding U.S. Weather Bureau Stations (Tables 17 and 18). Similarly, the mean monthly temperature (expressed in average degrees F.) for each county was taken from the monthly temperature records of at least three surrounding U.S. Weather Bureau Stations (Tables 17 and 19). These data were compiled from the U.S. Weather Bureau's Climatological Data, Michigan Annual Summary (1939-59). The selected stations were in close proximity to the study plots. It should also be mentioned that during the growing season all precipitation is effective in recharging soil moisture. There is no loss in the sandy soils of the study plots to surface run-off, regardless of rainfall intensity.

Potential evapo-transpiration

Most of the water that is stored in the soil or which falls on a given site is not used for tree growth but is returned to the atmosphere through evaporation and transpiration. The rate of evapo-transpiration is governed by two factors: (1) the atmospheric demand of existing

weather conditions such as temperature, wind, humidity, cloudiness, etc., and (2) the amount of soil water available for depletion. The atmospheric demand for water has been termed the potential evapo-transpiration. Zahner (1956) defines potential evapo-transpiration as ". . . the amount of water that will be lost from a land surface completely covered with vegetation if there is ample water in the soil at all times for the use of vegetation."

Direct measurements of potential evapo-transpiration are difficult. Many factors are involved: solar radiation, air temperature, atmospheric moisture, wind, and barometric pressure. However, an empirical relationship between potential evapo-transpiration and mean air temperature has been shown by Thornthwaite (1948). His method is based on the mean monthly temperature, heat index (the annual summation of long term mean monthly temperatures), day length, and the given month in a particular geographic location. The constants are the geographic position and heat index, while potential evapo-transpiration is the variable depending on temperature and time of year.

The monthly potential evapo-transpiration for each county during the period 1939-59 was calculated using the graphic technique of Thornthwaite's method, developed by Palmer and Havens (1958)(Table 20). The monthly potential evapo-transpiration is expressed in inches of water, as are the available water and precipitation.

Actual evapo-transpiration

Evapo-transpiration is met by the combined current precipitation and water stored in the soil. The potential rate can occur only when the soil is at maximum storage capacity. When this capacity is not maintained by precipitation, the amount of water supplied by the soil is re-

duced in proportion to the amount of available water left in the soil. Thus, the amount of water actually passing into the atmosphere does not equal the amount needed to meet the potential evapo-transpiration. As the soil water is depleted, the rate of actual evapo-transpiration decreases, because the remaining water is held ever more tightly by the tension forces within the soil.

Water deficits

The water deficit is the difference between the potential and actual evapo-transpiration. This deficit is a relative measure of the internal moisture stress on the vegetation. The calculation of the water deficit is an accumulative balancing of the potential evapo-transpiration (Table 20), precipitation (Table 18), and soil water within the limits of a soil series and the storage capacity of the root zone.

For this study of the shoot moth, the water deficit was calculated in inches of water for each study plot for each month of the study period (1939-59).—The procedures were developed by Zahner (1956). The monthly water deficit was found by subtracting the inches of precipitation from the potential evapo-transpiration and then adjusting for the water supplied from soil storage. Zahner (1956) provided tables for soils which stored over six inches of available water. In this study soils were encountered with storage capacities of only two inches and four inches; this necessitated extrapolating Zahner's soil storage supply table to include capacities below six inches (Table 21). During the months when precipitation is less than the potential evapo-transpiration, differences must be met by the stored soil water. The amount of water supplied from the soil depends upon the storage capacity of the root zone and the previous amount of water depletion. It should be noted

that as the soil becomes drier, it supplies proportionately less of the difference; also, the soil cannot usually equal the entire difference and soils with low storage capacities dry relatively faster than soils with high storage capacities.

Monthly water deficits were calculated by the above reasoning throughout the years 1939-59. Each rainfall recharge had to be accounted for regarding its part in lessening the deficits. Actual evapo-transpiration increases with each soil recharge by rainfall as more water is made readily available. To obtain the monthly water deficits for each study plot, curves were plotted for the available water ranging from one to twelve inches for each month from April through August during 1939-59 for the two study areas. From these curves the actual evapo-transpiration was estimated, from which the monthly water deficits for each plot were evaluated for each year of tree growth since planting.

The monthly water deficits were also expressed as percentages of the storage capacity--a most useful datum. Inasmuch as the water deficit varies disproportionately with the storage capacity of the root zone, the percentage of storage capacity permits the direct comparison of water deficits on soils throughout the range of storage capacities. This percentage is also a more sensitive index of the soil water-plant regime than the absolute water deficit. For example, the difference between potential evapo-transpiration and precipitation may be .52 inch of water. A soil with a storage capacity of two inches could supply .48 inch, leaving a water deficit of .04 inch. However, 1.52 inches of water remains in the soil. This would be seventy-six percent of the storage capacity. But a soil with a storage capacity

of eight inches would be able to completely supply the .52 inch difference, with 7.48 inches of water remaining in the soil. This would be ninety-four percent of the storage capacity. Thus a potential evapotranspiration demand of .52 inch would reduce a soil with a two-inch storage capacity to seventy-six percent, but only reduce to ninety-four percent a soil with an eight-inch storage capacity.

Statistical Analyses

In the initial stages of the analyses, graphs were drawn comparing the various environmental factors with the amount of shoot moth injury to the trees. These graphs indicated that the factors directly responsible for variations in tree damage included the age, height and growth rate of the tree, depth of rooting, amount of soil moisture, precipitation, and temperature during the months of larval feeding--and/or combinations of these factors. In order to discover which of these factors were exerting the greatest influence, various multiple regression analyses were used.[7]

First analysis

The first analysis used the multiple regression techniques on an IBM 650. A standard program was used. The four dependent variables that were tested expressed injury to the tree resulting from attack by the shoot moth. These were coded as:

Y1: The mean annual number of branches per whorl per plot
Y2: The percentage of trees forked per year per plot
Y3: The percentage of trees damaged by bushing (including posthorns and/or spikes) per year per plot
Y4: Y2 plus Y3

The independent variables believed to influence shoot moth damage were parameters of tree growth, soil moisture deficits, and weather. The variables expressing tree age, height, and rate of growth, were coded as:

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[7]I appreciate the advice, design, and work on the analyses by Dr. J.H. Bamping, Forestry Department, University of Georgia; Dr. J.L. Clutter, Biometrics Division, Southeastern Forest Experiment Station, U.S. Forest Service, and Dr. R.A. Schroeder, Computing Laboratory, Duke University.

X1: The age of the trees per plot since planting
X2: The mean annual total height of the trees per plot since planting
X3: The mean annual periodic height increment (internodal distance) of the trees per plot since planting

The influence of annual variations in site quality was analyzed as the water deficit, expressed in actual inches of water deficit and as the percentage of storage capacity. The soil moisture deficits were those occurring during the months of summer and spring feeding by the larvae. The monthly water deficits per year per plot were coded as X4 through X8 for April through August. The monthly percentages of storage capacity per year of tree growth per plot were coded as X9 through X13 for April through August. The possibility that temperature may directly influence the rate of development of the shoot moth in addition to its influence on water deficits was analyzed by coding the mean monthly temperatures per year per study area as X14 through X18 for April through August.

The predicting equations were not considered conclusive but they did aid in developing a more satisfactory analysis described in the next section. The first analysis revealed that the dependent variables of the mean annual number of branches per whorl (Y1) and the percentage of trees damaged by bushing (Y3) were of value for further correlations. Curvilinear functions were also discovered, necessitating some quadratic transformations.

Three plots (3,7 and 17) on which beech grass occurred were dropped. When tree injury was compared with the water-holding capacity of the root zone, it was apparent that the injury to the trees was much worse than would normally be expected. The size of the sample was too small to analyze the competitive influence of beech grass for available soil moisture.

Final Analysis

An IBM-7070 was utilized to solve the final regression equations. A standard program was used which calculates the regression equations in a series of steps, adding at each step the single most significant independent variable.[8] The status of each regression equation is known after each step of the regression: this includes the variables used, significance of the individual variables and also of the regression equation, the standard error of estimate, the multiple regression coefficient, and the degrees of freedom. The regression equation can then be chosen which has a minimum number of independent variables, yet additional variables will not materially affect the multiple correlation coefficient or the standard error of the estimate.

The dependent variables used to express shoot moth damage were defined as follows:

Y1: The mean annual number of branches per whorl per plot (x10)[9]
Y3: The percentage of trees damaged by bushing, posthorns and/or spikes per year per plot

The site factors believed to influence shoot moth damage were the soil water deficiencies during the months of larval feeding (expressed as the percentage of storage capacity) for two consecutive insect generations and the tree characteristics of age, height, and rate of growth. These data and their interactions were used as independent variables and were coded per plot as follows:

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[8]Dr. A - Multiple Regression Analysis (1961), available at the Digital Computing Laboratory, Duke University, Durham, North Carolina.

[9]Input data were scaled to range from .1 to 10.

Current insect generation

X 1:	April next year	percentage of storage capacity
X 2:	June current year	percentage of storage capacity
X 3:	July current year	percentage of storage capacity
X 4:	X2 X3	

Previous insect generation

X 5:	April current year	percentage of storage capacity
X 6:	June previous year	percentage of storage capacity
X 7:	July previous year	percentage of storage capacity
X 8:	X6 X7	

Tree characteristics

X 9:	Age since planting	
X10:	Mean annual total height	(x10)
X11:	Mean annual periodic height increment (internodal distance)	(x10)

Quadratics

X12:	$(X\ 1)^2$	
X13:	$(X\ 2)^2$	
X14:	$(X\ 3)^2$	
X15:	$(X\ 5)^2$	
X16:	$(X\ 6)^2$	
X17:	$(X\ 7)^2$	
X18:	$(X\ 9)^2$	
X19:	$(X10)^2$	(x100)
X20:	$(X11)^2$	(x100)

Temperatures affecting current insect generation

X21:	Mean April temperature next year	(x10)
X22:	Mean June temperature current year	(x10)
X23:	Mean July temperature current year	(x10)

Temperatures affecting previous insect generation

X24:	Mean April temperature current year	(x10)
X25:	Mean June temperature previous year	(x10)
X26:	Mean July temperature previous year	(x10)

CHAPTER V

RESULTS

Outbreaks of the shoot moth on red pine were found to be significantly associated with the age and growth rate of the tree, amount of soil moisture within the root zone, and summer temperatures. Tree injury in the form of reductions in the mean annual number of branches per whorl was associated with slowly growing trees, soils with low moisture content, and hot summer temperatures. Severe shoot moth damage resulting in bushing of the tree was also associated with low soil moisture levels and hot summer temperatures. The conclusion is reached that in Ottawa and Wexford Counties, Michigan, the tree is the primary natural mortality factor influencing populations of the shoot moth. The tree's resistance to attack by the shoot moth is influenced by the amount of water available within the root zone during the time when the larvae are feeding.

The selected regression equations explain between sixty and seventy-five percent of the variation in tree injury caused by the shoot moth, with acceptable errors of estimate. In a statistical sense, the null hypothesis is rejected that shoot moth damage is not associated with site quality for red pine.

These results are presented in detail in the following sections:

Branches Per Whorl

A reduction in the number of branches per whorl in a red pine plantation infested with the shoot moth is usually a reflection of the extent of larval feeding in the lateral buds of the terminal bud cluster. An increase in this type of injury is associated with slowly growing trees, consecutively hot summers, and low levels of soil moisture. There is no sharply marked point where injury to the tree begins. However, the arbitrary limit set as an indication of outbreak conditions is when the number of branches per whorl are two or less for one or more years and when stem deformity occurs on more than forty percent of the trees (Talerico and Heikkenen, 1962). It is important to note that reductions in the branches per whorl to two or less occur only when the percentage of the available water storage capacity within the root zone has dropped to approximately forty percent or less in July (Tables 24, 25 and 26).

It should be mentioned again that the monthly percentage of storage capacity is a more sensitive indicator of the soil water-plant regime than the absolute water deficit. When the available soil moisture is expressed as a percentage of the storage capacity of the root zone, it permits a direct comparison of soil moisture deficits occurring in different soils at various times; and it also reflects the disproportionate influence of actual evapo-transpiration and soil recharge throughout the range of storage capacities (see example, page 32).

The water deficit is accumulative, a continuing measure of the soil moisture available for tree growth. Thus the percentage of the storage capacity in July also represents the influence of the preceding months of April, May and June.

Ottawa County

In Ottawa County reductions in the mean annual number of branches per whorl (Y1) were associated with these independent variables:

Current insect generation

X 3: July current year percentage of storage capacity
X22: June temperature current year

Previous insect generation

X24: April temperature current year
X26: July temperature previous year

Tree characteristics

X 9: Age since planting
X11: Mean annual internodal distance

This predicting equation was selected because additional variables did not materially affect the multiple correlation coefficient or the standard error of the estimate:

$$Y1 = 15.455 + .0152\ X\ 3 - .167\ X\ 9 + .207\ X\ 11 - .087\ X\ 22 - .069\ X\ 24 - .0729\ X\ 26$$

Multiple correlation coefficient	(R)	= .7789
Coefficient of determination	$(R)^2$	= 60.67 %
Standard error of the estimate		= .951 branches
F - value (6 and 364 d.f.)		= 93.58**

When the predicting equation is presented in tabular form, the relations between the variables are more readily grasped (Table 24). To illustrate, during the outbreak years of 1955-56 in Ottawa County, the mean monthly temperatures were:

X26: July previous year (1955) = 76.9° F.
X24: April current year (1956) = 44.0° F.
X22: June current year (1956) = 69.2° F.

These variables have partial predicted negative values of -8.8 and -6.0 respectively in Table 24. During 1956, to predict that a ten-year-old red pine would have more than two branches per whorl, the tree must have

an internode exceeding twelve inches and be growing on a site having more than forty percent of the storage capacity during July. But in 1957-58, when the tree damage was not as severe in Ottawa County, the mean monthly temperatures were:

X26: July previous year (1957) = 72.2° F.
X24: April current year (1958) = 47.6° F.
X22: June current year (1958) = 61.5° F.

These variables have a partial predicted value of -8.4 and -5.3 (Table 24). Thus, in 1958, only those ten-year-old red pines growing six inches or less on sites with less than twenty percent of storage capacity in July would have been predicted to have less than two branches per whorl. Thus only on very poor sites with very low water-holding capacities could a shoot moth outbreak continue during these relatively cool seasons.

Wexford County

In Wexford County, as in Ottawa County, the attacks by the shoot moth on the lateral buds were also associated with slowly growing trees and low levels of soil moisture. Reductions in the mean annual number of branches per whorl (Y1) were associated with these variables:

Tree characteristics

X 9: Age since planting
X11: Mean annual internodal distance

Soil moisture

X 7: July previous year percentage of storage capacity

The selected predicting equation is:

$$Y1 = .367 + .027\ X\ 7 - .0987\ X\ 9 + .212\ X\ 11$$

Multiple correlation coefficient	(R)	= .8703	
Coefficient of determination	$(R)^2$	= 75.74	%
Standard error of the estimate		= .888	branches
F - value (3 and 227 d.f.)		= 236.20**	

The branches per whorl in plantations infested by the shoot moth can also be predicted when the equation is presented as a table (Table 25). Again it is important to note that reductions in the number of branches per whorl to two or less occur when the percentage of storage capacity approaches forty percent or less during July. From this we may conclude that outbreaks of the shoot moth do not occur when adequate soil moisture is present.

Bushing

Very heavy infestations result in the destruction of all buds in the terminal cluster. The result is the development of bushes, spikes, or posthorns. In the statistical analysis, all these types of damage were grouped together and designated as "bushing". When bushing and other stem defects, such as forking, occur on forty percent of the stems, populations of the shoot moth are considered to have reached outbreak numbers (Talerico and Heikkenen, 1962). Again it is important to observe that this type of injury to the tree in Ottawa County is associated with storage capacities of forty percent or less within the root zone (Table 26). In Wexford County the amount of bushing was too small to provide a sample of adequate size. In Ottawa County, the percentage of trees annually bushed was associated with these variables:

Current insect generation

X 2: June current year — percentage of storage capacity
X 3: July current year — percentage of storage capacity
X 4: X2 X3
X22: June temperature current year

Previous insect generation

X 5: April current year — percentage of storage capacity
X 6: June previous year — percentage of storage capacity
X 7: July previous year — percentage of storage capacity
X 8: X6 X7

Quadratics

X15: $(X5)^2$
X16: $(X6)^2$

This predicting equation was selected:

$$Y3 = 106.855 - .254 X 2 - .644 X 3 + .0069 X 4 - 2.138 X 5 - 1.687 X 6 - .725 X 7 + .008 X 8 + .0151 X 15 + .0111 X 16 + .819 X 22$$

Multiple correlation coefficient	(R)	= .8252	
Coefficient of determination	$(R)^2$	= 68.10	%
Standard error of the estimate		= 15.690	%
F - value (10 and 360 d.f.)		= 76.81**	

This predicting equation has also been put in tabular form (Table 26).

Susceptible Sites

Outbreaks of the shoot moth appear to be possible only when the percentage of the storage capacity within the root zone is reduced to forty percent or less during the summer feeding period of the larvae. Root zones with storage capacities of less than two inches are reduced below forty percent in all but the coolest and wettest summers (Tables 27, 28 and 29). On these areas red pine damage may be expected year after year. When the storage capacity of the root zone is approximately four inches, reductions below forty percent occur during summers of average or below average precipitation. If the storage capacity is approximately six inches, tree damage by the shoot moth can occur only during extreme drougnts. Shoot moth damage has not occurred on soils with a storage capacity of eight or more inches in Ottawa and Wexford Counties, Michigan. If free water is continuously available, as when a ground water capillary fringe extends into the root zone, the tree is not damaged by the shoot moth regardless of the storage capacity of the root zone.

The factors believed to influence the percentage of the storage capacity were analyzed. The dependent variable was the percentage of the storage capacity within the root zone during the months of larval feeding (Y). The independent variables were the mean monthly temperatures and precipitation, and the water storage capacity within the root zone for each study plot. The data were coded as:

Dependent variables

Y: The percentage of storage capacity during the most significant month affecting shoot moth damage (Tables 24, 25 and 26).

Independent variables

Temperature:

X 1: Mean March temperature per study area
X 2: Mean April temperature per study area
X 3: Mean May temperature per study area
X 4: Mean June temperature per study area
X 5: Mean July temperature per study area

Precipitation:

X 6: Mean March precipitation per study area
X 7: Mean April precipitation per study area
X 8: Mean May precipitation per study area
X 9: Mean June precipitation per study area
X10: Mean July precipitation per study area

Storage capacity:

X11: Storage capacity of the root zone per plot

Ottawa County

In Ottawa County June and July were the months when soil moisture had the most significant effect upon the shoot moth (Tables 24 and 26). In June the percentage of storage capacity was associated with:

X 2: Mean temperature in April
X 8: Mean precipitation in May
X 9: Mean precipitation in June
X11: Storage capacity of the root zone

The predicting equation was:

$$Y = -123.984 + 1.898\,X_2 + 7.886\,X_8 + 13.631\,X_9 + 8.295\,X_{11}$$

Multiple correlation coefficient	(R)	= .7770	
Coefficient of determination	$(R)^2$	= 60.37	%
Standard error of the estimate		= 16.07	%
F - value (4 and 366 d.f.)		= 139.44**	

This equation is presented in tabular form in Table 27.

During July in Ottawa County the percentage of storage capacity was associated with:

X 3: Mean temperature in May
X 9: Mean precipitation in June
X10: Mean precipitation in July
X11: Storage capacity of the root zone

The predicting equation was:

$$Y = 106.521 - 2.206\ X\ 3 + 3.472\ X\ 9 + 6.767\ X\ 10 + 7.100\ X\ 11$$

Multiple correlation coefficient	(R)	=	.7339
Coefficient of determination	$(R)^2$	=	53.86 %
Standard error of the estimate		=	15.43 %
F - value (4 and 366 d.f.)			106.83**

This equation is presented in tabular form in Table 28.

Wexford County

In Wexford County July was the month when the percentage of the storage capacity had the most significant effect on tree damage by the shoot moth (Table 25). The variables influencing the water deficit were:

X 6: Mean precipitation in March
X 9: Mean precipitation in June
X10: Mean precipitation in July
X11: Storage capacity of the root zone

The predicting equation was:

$$Y = -33.597 + 9.181\ X\ 6 + 5.969\ X\ 9 + 6.514\ X\ 10 + 7.290\ X\ 11$$

Multiple correlation coefficient	(R)	=	.8163
Coefficient of determination	$(R)^2$	=	66.64 %
Standard error of the estimate		=	12.22 %
F - value (4 and 226 d.f.)		=	112.86**

This predicting equation is presented in tabular form in Table 29.

Prediction of Susceptible Sites

Determination of storage capacities

Because severe tree damage by the shoot moth is closely associated with the water-holding capacities of the root zone, those factors influencing the storage capacities of the root zone were examined. Scatter diagrams readily revealed the close association of the soil storage capacity with the depth of rooting. The storage capacities can be predicted for the following soil series in Ottawa and Wexford Counties, Michigan, if the maximum depth of rooting is known:

1. AuGres
2. Saugatuck
3. Rubicon
4. Kalkaska

When the storage capacity of the root zone (Y) is the dependent variable and the maximum depth of rooting, in inches, is the independent variable (X), the predicting equation is:

$$Y = 6.311 (\log_{10}X - 5.981)$$

Correlation coefficient	$(R)_2$	= .9381	
Coefficient of determination	$(R)^2$	= 88.00	%
Standard error of estimate		= .67	inches
F - value (1 and 47 d.f.)		= 344.88**	

This equation is presented in tabular form in Table 30.

Factors influencing depth of rooting

The maximum depth of red pine roots is influenced by a few dominant factors. From observations on the sixty-five trees sampled in Ottawa and Wexford Counties, the dominant factors in the sandy soils appear to be: (a) age, (b) degree of wind erosion, (c) presence of a hard pan, (d) depth to free water, (e) structural differences (gravel bands). These factors are discussed in the following paragraphs.

Age of tree.--From personal observations it appears that the maximum depth of rooting may be reached within five years after planting, with the roots descending approximately one foot per year in sandy soils. Williams (U1958) believes the time to be ten years. Stoeckeler and Limstrom (1942) have reported the growth rates of roots to vary with size of planting stock in the sandy soils of Wisconsin. A depth of approximately twenty-two inches was reached one year after planting 2-2 red pine, 2-1 stock reached seventeen inches, and 2-0 stock descended ten inches.

Degree of erosion.--In this study six plots were wind-eroded to the "C" horizon on Rubicon (3 plots), Kalkaska (2 plots), and Blue Lake (1 plot) soil series. The maximum depth of rooting ranged from ten to twelve inches ($\bar{X}$ = 11.7 inches). On adjacent non-eroded soils, roots descended to greater depths. The reason is not known for the shallow rooting.

Cemented hard pan.--Red pine roots apparently will not penetrate a cemented hard pan. Three soil profiles were examined in the Saugatuck soil series. The roots descended to the proximity of the hard pan but did not penetrate.

Free water.--A total of twenty-three plots had free water or mottling streaks within twelve feet of the surface. Roots descended to the proximity of the water or mottling, with the exception of the three plots with cemented hard pans (Saugatuck soil series). The number of plots per soil series were:

AuGres	(8)	Saugatuck	(3)
Rubicon	(5)	Kalkaska	(2)
Croswell	(4)	Antrim	(1)

The depth of rooting (Y) can be predicted if the depth of free water or mottling (X) is known. The three plots with cemented hard pans were not used to determine the depth of rooting to free water.

The predicting equation is:

$Y = .942\ X - 8.321$

Correlation coefficient	(R)	= .9013	
Coefficient of determination	$(R)^2$	= 81.23	%
Standard error of estimate		= 11.02	inches
F - value (1 and 18 d.f.)		= 77.91**	

This equation is presented in tabular form in Table 31.

Structural differences.--There is some association between the occurrence of texture-gravel bands and the depth of rooting in Ottawa and Wexford Counties, Michigan. When these bands occur together, the deeper lying band is associated with the maximum depth of rooting. This phenomenon was observed in these soil series:

Rubicon	(15)	East Lake	(3)
Kalkaska	(9)	Free Soil	(1)
Graycalm	(3)		

The predicting equation to determine the depth of rooting (Y) from the depth to texture-gravel bands (X) is:

$Y = 36.616 + .463\ X$

Correlation coefficient	(R)	= .4813	
Coefficient of determination	$(R)^2$	= 23.17	%
Standard error of estimate		= 14.70	inches
F - value (1 and 28 d.f.)		= 8.44*	

This equation is presented in tabular form in Table 32.

Overburden.--An overburden (wind-deposited soil) occurred on nine plots. In all but one plot rooting depth was closely associated with the sequence of dominant factors: hard pan, free water, and texture-gravel bands. The plots were on the Rubicon (8) and the Saugatuck (1) soil series.

Pure sand.--Only two plots were "pure" sand--that is, there was no wind erosion, hard pan, mottling, free water, or textural-gravel bands within twelve feet of the surface. One plot occurred on a Rubicon sand and one on a Kalkaska sand. The maximum rooting depths were twenty-four and thirty-six inches on these plots.

Insect-Host Interactions

Pointing (U1963) has estimated that a larva eats 1.62 buds during summer and about 2.5 buds (Heikkenen, U1958b) during the spring. In Michigan, an effort has also been made to estimate the amount of bud damage by shoot moth larvae. Composite trees based on the mean tree were collected in nine different red pine areas after the summer feeding period and in five of these areas following the spring feeding period. The insect population was determined for these areas and the number of totally and partially damaged buds were counted. Allowances were made for dead larvae. It is important to note that the average insect population per composite tree ranged from 8 to 101 after summer feeding, and 10 to 43 after spring feeding. The age of the trees varied from ten to thirteen years. The predicting equation for the number of buds (Y) destroyed by the average summer feeding larva (X) is:

$$Y = - 125.517 + 139.559 \log X$$

Correlation coefficient	(R)	= .9431	
Coefficient of determination	$(R)^2$	= 88.95	%
Standard error of estimate		= 17.00	buds
F - value (1 and 7 d.f.)		= 56.37**	

The predicting equation to determine the number of buds destroyed (Y) by a larva feeding in the spring (X) is:

$$Y = - 41.813 + 84.309 \log X$$

Correlation coefficient	(R)	= .9202	
Coefficient of determination	$(R)^2$	= 84.68	%
Standard error of estimate		= 9.90	buds
F - value (1 and 3 d.f.)		= 16.58*	

These equations are presented in tabular form in Table 33.

The significance of the number of buds destroyed during the period of summer feeding is immediately apparent when related to the level of the shoot moth population in the summer and the following

spring. Apparently more than eighty percent of the shoot moth damage to red pine is caused by the summer feeding of early instar larvae. This is of importance when evaluating the influence of the insect upon the tree, timing insecticide applications to prevent tree damage, and studying the factors influencing the resistance of the tree to shoot moth attack

During this study observations indicated that red pine growing on sites of different quality had widely different patterns of shoot growth. Rapidly growing red pine appeared to have a greater number of shoots than slow-growing red pine of the same age. This suggested that the quality of the site for red pine may have a great influence on the insect's food and shelter supply. In an effort to determine the influence of site quality upon the amount of shoot growth, the number of shoots were counted on 137 trees in nine plantations not infested with the shoot moth. The ages of the trees ranged from four through seventeen years. The results of this study clearly indicated that the number of shoots (Y) produced by red pine can be predicted from the height of the tree (X).

The predicting equation is:

$$\log Y = .6487 + .0197 X$$

Correlation coefficient	(R)	= .8418	
Coefficient of determination	$(R)^2$	= 70.87	%
Standard error of estimate		= 43.71	shoots
F - value (1 and 135 d.f.)		= 328.42**	

This equation is presented in tabular form in Table 34.

The influence of red pine site quality upon the food supply and shelter for the shoot moth is readily apparent. If a young red pine is ninety-six inches tall, it has 346 shoots, but only 40 shoots will develop on a tree forty inches tall. If both trees are infested with

one hundred shoot moth larvae, the tall tree would have some undamaged shoots. On the short tree, larval competition may occur. Population levels without reference to the amount of food and shelter are meaningless. However the influence site quality may have on the amount of food and shelter has yet to be considered in any study of the population dynamics or control of the shoot moth

CHAPTER VI

DISCUSSION

Theory of Natural Control

Research in forest entomology is frequently directed toward the insect, rather than to the host trees and their environment. Yet it is interesting to observe the great volume of timber which is not seriously damaged, although destructive insects are present in every forest. This is the old problem of what causes the natural limitation in the number of these ever-present insect pests.

Numerous theories exist to explain the natural control of insect populations. Theories range from the simplified concepts of the dominant role of isolated control factors, such as weather or parasites, to the complex concepts of the simultaneous influence of all the elements of the ecosystem. Research based on these theories has not explained adequately the population fluctuations of the shoot moth. Past studies of isolated factors did not solve the problem of the shoot moth and the broadness of the ecosystem approach has prevented its use in the field.

An answer to this dilemma has recently been proposed. Lawson (1958) believes that within the ecosystem an inherent limitation exists in the number of enemies attacking a given host. He points out that only a very few enemies exercise significant natural control, exerting their dominance in a definite sequence. To Lawson's ideas may I add that the key to an understanding of natural control lies in a rearrange-

ment of our concepts of the ways the few significant natural control factors permit the outbreak of a specific insect population. Three broad prerequisites must be satisfied for the occurrence of an insect outbreak:

First: A susceptible host condition must exist for the specific insect pest.

Second: A condition must be present which will "release" the expansion of the insect population.

Third: Conditions must be favorable for the rapid development of the insect population.

These three prerequisite conditions are distinct and must occur in sequence to permit an outbreak. The solution of problems in forest entomology depends on the identification of the few significant natural control factors affecting a specific insect pest within each of the three prerequisite conditions. In this arrangement the specific tree host is primary. A distinction must also be made between the release condition and the conditions influencing the rate of development of an insect population.

Past failures to prevent or control outbreaks of the shoot moth were not because of a lack of studies on insect biology or conditions influencing the rates of development of insect populations. Failures have been caused by an almost total omission of research on susceptible host conditions or the condition which releases an insect outbreak.

Susceptible host condition

A susceptible host condition for the shoot moth occurs when red pine is subjected to water stress during the summer. This water stress within the tree is chiefly a function of the water capacity of the root

zone which, in turn, is a function of depth of rooting and weather conditions, especially temperature and precipitation. (See Results: Susceptible Sites).

Shoot moth outbreaks in Ottawa and Wexford Counties, Michigan, occur when red pine is growing under internal moisture stress. Such stress occurs only on sites where by July the percentage of the storage capacity of the root zone can be reduced to forty percent or less. During drought periods in the summer, this occurs on sites with storage capacities of six inches or less. This water-holding capacity is associated with rooting depths that are usually less than seventy-eight inches (Table 30). On such soils red pine is susceptible to outbreaks of the shoot moth. The following tree and soil conditions were found associated with shallow rooting depths:

1. Trees less than five years old
2. Soils wind-eroded to the "C" horizon
3. Cemented hard pans
4. Free or fluctuating water close to the surface
5. Soils without stratified texture-gravel bands

The influence of free water is deceptive. When the water table is near the surface, the early height growth of red pine is rapid. But if the water table drops, only water stored within the root zone is available for tree growth. The root zone is often quite shallow and not capable of holding more than a few inches of water. It must be remembered that the crown has grown under conditions of ample soil moisture. When the trees are subjected to extreme drought conditions, soil moisture is rapidly depleted through evapo-transpiration. The growing conditions can thus be altered drastically in a short period of time during a single season. The average depth of the ground water table can be determined readily by the presence of mottling streaks in the soil profile. In the

sandy soils of Ottawa and Wexford Counties the streaks are yellow-orange (10YR6/4) in color.

The presence of textural bands is often responsible for the occurrence of the "islands" of lightly damaged trees amidst severely damaged trees (Fig. 8). These bands probably account for much of the variation in shoot moth attacks in Ottawa County, Michigan. The majority of damaged red pine grows on soils formed during the Calumet stage of Glacial Lake Chicago. But little tree injury occurs in the plantations growing on the lake bed of the Glenwood stage of Glacial Lake Chicago. During the Glenwood stage, the Grand River discharged into Glacial Lake Chicago, producing the Allendale Delta (Bretz, 1951). This delta suggests that large quantities of sediment were being discharged and laminated with the lake sands. The resulting texture-gravel bands in these soils are associated with deep root systems and the trees are relatively free of shoot moth damage.

The significance of the deep-lying textural bands has been recognized by the U.S. Soil Survey. Several new soil series have been based upon this characteristic, for example, the Greycalm series in sandy soils.

However, during the Calumet stage of Glacial Lake Chicago, no delta occurred at the mouth of the Grand River. The lake beds formed in a quite, shallow lake with few deposits of clay or gravel. Zumberge and Potzger (1956) report a minimum of wave agitation at this time. These "pure" sands are the areas where severe damage from the shoot moth now occurs in Ottawa County. The majority of red pine in these areas are shallow rooted.

The association of the depth of rooting with texture bands has also been observed by Van Eck (U1958). In a red pine plantation with a site index higher than average for a Rubicon sand, sinker roots ". . . descended to the bands of finer sand between the 36 and 48 inch depth." Van Eck also reports red pine roots descending to gravel layers one hundred inches deep. Deep-lying fine soil layers have also been reported by White and Wood (1958) as being associated with rooting at a depth of six to seven feet, but not to a depth of nine to ten feet. However, in this same plantation variations in the growth of red pine have also been associated with past land use patterns of cultivation and the resulting soil fertility levels (Heiberg and Loewenstein, 1958).

Release condition

The second prerequisite for an insect outbreak is a factor which releases the insect's rate of development. The release factor for an outbreak of the shoot moth on red pine is the condition of the pine needle. No natural control occurs when the tree is under moisture stress. This theory is based on the fact that oviposition studies have shown that eggs are laid on adjacent areas of lightly and severely damaged red pine (Tables 1 and 2). Bud damage occurred on the severely damaged trees, but not on the lightly damaged trees. It is believed that differential larval mortality occurred before the larvae attacked the buds. This mortality most likely occurred during the needle-mining stage.

Biological studies of the shoot moth were begun during 1958 in Michigan by Miller and Heikkenen. These studies are continuing. During 1958 we found extensive larval mortality to occur in one instance during the needle-mining period on rapidly growing red pine. However, little

larval mortality occurred during this time on slowly growing red pine. The detection of larval mortality during the needle-mining period is based on an accurate egg count.

How variations in spring and summer weather specifically create a susceptible host condition for the shoot moth is not known. An actual mortality factor may be involved. In Belgium, Voûte and Walenkamp (1946) state that:

> ". . . in situations where the moisture is sufficient, living trees have a natural resistance against infestation by Evetria (=Rhyacionia) buoliana. This resistance is associated with the ability of the tree to produce resin. Our observations cannot support this because the young larvae did not even try to bore in. Therefore they could not come in contact with the resin.
>
> "More important. . . is the way in which the climate gives resistance to the tree against the attacks of the newly hatched larvae; the drier the tree, the greater the chance that the newly hatched larvae can bore themselves into the needles."

What effect the needle actually has upon the first instar larvae is not known. Pointing (U1963) has found that the establishment success of newly hatched larvae varies considerably with years and trees; between 1955 and 1961 the total mortality of needle-feeding larvae ranged from thirty-two to seventy-two percent. In Michigan, Haynes (U1960) reports that during the needle-feeding period larval mortality may be over eighty percent before the larvae enter the buds. Mortality of first instar larvae may be associated with the possibility that there may be no exudation of resin when the available soil water is in the lower half of the range of readily available soil moisture (Kramer, 1941), or that the base of newly expanding needles becomes lignified when the tree is under moisture stress (Larson, 1963).

The effects of variations in summer weather upon the shoot moth are well established. In Belgium, Voûte and Walenkamp (1946) were the first to report that outbreaks were associated with dry Julys. Neugebauer (1952) in Germany agrees with this observation. The first report of the association of hot, dry summers in the United States followed the re-examination of the first Connecticut outbreak (Heikkenen, U1960). The Connecticut outbreak, the 1950 Ohio, and the mid-1950 Michigan outbreaks were shown to be closely associated with hot, dry summers by Talerico and Heikkenen (U1960a). The significance of hot, dry summers is also shown in this study.

Conditions affecting rate of development

Once a susceptible host condition exists and the insect's rate of development is released, the third prerequisite of favorable conditions for the development of the insect must be present. The shoot moth is capable of a rapid rate of increase. Pointing (1961) reports a mean fecundity of 116 eggs. If these eggs survive, the larval population is capable of severe tree damage. Even a small population of the shoot moth may be a serious problem. When an infestation exceeds seven insects per tree (spring count), all trees in a plantation will be infested (Miller, 1960).

The time period required for the occurrence of an outbreak of the shoot moth is not known. Voûte and Walenkamp (1946) believe an outbreak can occur in one year. In the United States and Canada, two years may be needed for the occurrence of an outbreak. This time interval was needed to obtain significant associations of damage of red pine by the shoot moth with environmental factors (Tables 24, 25 and 26).

It appears that the rate of development of the shoot moth is increased by warm summers, but retarded by cool springs and summers (Williams, U1957, and Pointing, 1961). However in England Harris (1960a) suggests that shoot moth survival is associated with the development of resin canals in the buds. He believes the development of resin canals depends on day length, while insect development depends on temperature. Thus, in hot summers the insect develops early and attacks the buds before the resin canals are fully developed. But in cool summers, development of the larvae is delayed and the insect attacks the buds after the resin canals are developed.

Harris' theory of differential insect development and stable tree development does not hold for red pine. Pointing (1961) has found that cool, wet weather delays both the shoot growth of red pine and the flight period of the shoot moth. Thus, the two phenomena remain synchronized. Evidence supporting Pointing's observations of annual variations in the length of the red pine growing season has been reported by Cook (1941) and Farnsworth (1955). Harris also reports that during cool summers, larvae were found attacking Scots pine buds in August and September. This may be the case in England; but Pointing (U1963) has found that the larvae in Ontario, Canada, stopped feeding by the first week of August. This observation was replicated in Michigan by Haynes (U1960).

Prevention and Control

Economic aspects

Opinions vary on the economic importance of attacks by the shoot moth. Previous American opinion has held that the shoot moth is capable of destroying red pine plantations as economic units. However in England, Greenfield (1914) has summarized quite well the course of an outbreak and its forestry implications.

> "do not therefore let the estate owner or his young forester despair when his most promising Scots fir plantation is selected for a home by this little moth, but let him avoid rushing into what may be needless expense. Patience is required; certainly for a few years the plantation may seem to be in a bad way, and especially so if the infestation is a severe one, because only few trees escape, and many will be attacked several times. However, in two or three years after the first attack, the infestation will be at its worst, and then generally will gradually decline and die out. Then is the time for the forester to step in with his pruner and thus lessen to the best of his ability the damage done by the sluggish brown caterpillars. When the pruning is done, patience is still required, but after two years the shoots left will be going ahead, and in a few years time, the kinks in the stems will, more or less, straighten out."

The economic loss will vary with the intended product. Damage by the shoot moth may destroy a tree for a telephone pole or degrade a sawlog, but not destroy a pulp stick. And pulp losses will vary with the length of the stick. When the 1930 Connecticut outbreak was re-examined (Heikkenen, U1960), there were approximately 240 straight stems per acre at Rose Pond (Table 35, Plantation I). This is a sufficient number of trees for a well stocked sawlog stand. The data in Table 35 may be misleading; Plantation I had been thinned prior to my cruise in 1958, and a few trees had been cut in Plantation II. In Germany, Wagenknecht (1941) found that after an outbreak there was a sufficient number of straight stems (40 percent) to provide a closed, merchantable stand.

In the Connecticut outbreak the majority of trees were damaged only once. During 1958, thinnings from these stands were sold in 4-foot sticks (three-inch top) by the ton. If all damaged trees were sold and all forks and crooks less than two inches were not culled, only seven 4-foot sticks with crooks of more than four inches would be lost in Plantation I and sixteen 4-foot sticks in Plantation II (Table 36). In Michigan, similar stem damage was found in four young red pine plantations by Talerico and Heikkenen (1962).

The possibility exists that the shoot moth may cause a considerable loss in pulp yield. Reduced fiber length and compression wood may result from fork and crook in the main stem.

Direct control

The effectiveness of direct control methods for the European pine shoot moth which will prevent tree damage remains subject to further research. Extensive insecticide tests, conducted by Miller and Haynes (1961), have reduced shoot moth populations by as much as ninety-nine percent. Yet, when the annual height increment and branches per whorl before, during, and after the year of treatment and also the total heights, were compared with the non-treated plots, no significant effects could be detected in tree growth by Talerico and Heikkenen (U1960b). However, Miller redesigned the analysis, compared deviations of plot means with plantation means using a linear regression model, and found that on summer treated plots tree growth was improved (Talerico et. al. U1963). Complete suppression of the shoot moth resulted in a fifty-five percent increase in the following year's height growth and a sixty-six percent increase in the number of branches per whorl. No differences were found on spring treated plots.

Silvicultural control

Shoot moth damage occurs in Ottawa and Wexford Counties, Michigan when the tree is subjected to internal moisture stress. This occurs when the water deficit in July is so severe that the percentage of available soil moisture falls below forty percent for two consecutive years. It is possible to estimate the water-holding capacity of the root zone because it is closely associated with the depth of rooting (Table 30).

To prevent perennial shoot moth damage to red pine, the tree should not be planted on soils where the root zone holds less than two inches of water. On these soils the drought limits for red pine in shoot moth infested areas are exceeded nearly every year. This condition occurs in Ottawa and Wexford Counties on:

1. Sandy soils wind-eroded to the "C" horizon.
2. Sandy soils where the root zone is restricted to 18 inches by a hard pan or free water. These conditions are found on the AuGres and Saugatuck soil series.

Occasionally severe outbreaks of the shoot moth occur on red pine during drought periods on soils capable of storing more than two inches but less than six inches of water within the root zone--this occurs when the roots do not reach a depth of more than seventy-eight inches. Shallow rooting occurs where a fluctuating water table is within six feet of the surface and texture-gravel bands do not occur within ten feet of the surface. Damage can be avoided by not planting red pine on these soils.

Other pine species are more resistant to the shoot moth than red pine. In Ottawa County, three broad susceptibility classes exist for eight pine species (Miller and Heikkenen, 1959). The most susceptible

species is red pine. In the medium susceptibility class are Austrian, ponderosa, and Scots pine. The low susceptibility class includes white, jack, Virginia, and pitch pine. On sites with water-holding capacities of less than four inches, the best species for Ottawa and Wexford Counties, Michigan, is probably jack pine.

CHAPTER VII

SUMMARY

A highly significant association exists between red pine site quality and the severity of damage by the European pine shoot moth. This study describes the development and testing of the hypothesis that the resistance of red pine to attack by the shoot moth is proportionate to site quality as measured by soil water factors.

An outbreak of an insect species on a given host is governed by three prerequisite conditions. All three must be favorable and operate in sequence to permit an outbreak. The three prerequisites are: (1) a susceptible host condition, (2) the release condition, (3) favorable conditions for the insect's rate of development.

The primary prerequisite for an outbreak of the shoot moth on red pine is a susceptible host condition. Red pine is susceptible when growing under internal water stress. This stress is associated with soils where the soil water deficit is less than forty percent of the storage capacity of the root zone. This condition must occur for two consecutive years during the summer feeding period of the larvae. The relation of tree damage by the shoot moth with soil moisture deficits, in turn, emphasizes the importance of the water-holding capacity of the root zone, precipitation, and evapo-transpiration. This study found the water-holding capacity of the root zone in the sandy soils of Michigan to be significantly associated with the depth of rooting which can be predicted if the degree of erosion, presence of a

cemented hard pan, level of the water table, and the presence of texture-gravel bands are known. The water-holding capacity of the root zone determines where a susceptible host condition for an outbreak of the shoot moth can occur. Shoot moth outbreaks do not occur where the root zone has a water-holding capacity of more than six inches. Perennial damage to the tree occurs on sites of less than two inches. Between two and six inches of water-holding capacity, outbreaks of the shoot moth can occur only when spring and early summer temperatures are above normal and precipitation below normal for two consecutive years.

The second prerequisite for an outbreak is the occurrence of a release factor. In this study the conclusion is made that the release factor is the red pine needle. When the needles are subject to moisture stress, early instar larvae are able to complete the needle-mining stage and then attack the buds. But if the tree is growing under adequate moisture conditions, extensive mortality occurs during the needle-mining period and little damage occurs to the buds.

The third prerequisite for a shoot moth outbreak is favorable conditions affecting the insect's rate of development. These climatic conditions are always present throughout Ottawa and Wexford Counties, Michigan. Evidence of this condition are the areas of perennially damaged red pine.

The majority of damage to red pine occurs during the summer. An early instar larva destroys nearly the same number of buds as a late instar larva. Thus, the higher population levels during the summer account for the majority of tree damage. The destruction of buds deforms the tree. The resulting cull varies with the site quality and utilization practices. The majority of damage is correctable by pruning. There are

very few unmerchantable pulp sticks. However, the possibility exists that a loss may occur in pulp yield. There are usually a sufficient number of straight stems following an outbreak to provide a well stocked stand. Site quality for red pine also influences the food and shelter supply for the shoot moth. There are more shoots on a rapidly growing tree than on a slow-growing tree of the same age. This has a decided effect on the destructiveness of a given insect population.

Silvicultural methods to prevent shoot moth damage conclude the study. These are especially important because of the ineffectiveness of chemical controls to prevent tree damage. Red pine should not be planted on soils where the root zone will hold less than four inches of water. This condition occurs on soils eroded to the "C" horizon or the root zone is restricted to eighteen inches by a hard pan, bed rock, or free water. Red pine will be occasionally damaged on soils where the root zone can store less than six inches of water. Damage can be avoided on these sites by not planting red pine where the roots will reach a depth of less than seventy-eight inches. Shallow rooting occurs where a fluctuating water table is within six feet of the surface and texture-gravel bands do not occur within ten feet of the surface. Where red pine is not recommended, jack pine should be planted.

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TABLE 1.--Oviposition of the shoot moth in 1958 in adjacent areas of lightly and severely damaged red pine.

Plantation	County in Michigan	Mean number eggs per shoot[a]	
		Lightly damaged trees	Severely damaged trees
1	Ottawa	.4 ± .8	.9 ± .9
2	Wexford	1.7 ± 2.3	2.1 ± 1.9

[a]The sample shoots were selected at random from the top whorl. Size of sample ranged from 10 to 30 shoots, one shoot per tree.

TABLE 2.--Oviposition of the shoot moth in 1959 in adjacent areas of lightly and severely damaged red pine.

Plantation	County in Michigan	Mean number eggs per mean tree[a]	
		Lightly damaged trees	Severely damaged trees
1	Ottawa	122 ± 52	44 ± 31
2	Wexford	20 ± 9	110 ± 57
3	Oceana	124 ± 9	168 ± 5

[a]The sample represents a composite tree based on the mean annual branches per whorl per plot. From a random starting point, a single branch per tree was taken for each branch of the composite tree; thus many individual trees contributed to the composite tree sample. Size of sample ranged from 2 to 4 composite trees per plot.

TABLE 3.--Geologic features and associated soil series in Ottawa and Wexford Counties, Michigan

OTTAWA COUNTY

Geologic feature	Soil drainage	
	Well-drained	Imperfectly drained
	Soil series	
Dune sands	Bridgeman (now Deer Park and Rubicon)	---
Lake sands	Plainfield (now Rubicon)	AuGres, Saugatuck

WEXFORD COUNTY

Moraine	Kalkaska Rubicon	---
Till plain, or outwash plain	Rubicon	---
Melt water channel	Rubicon Grayling	---

Blanks (---) indicate series not included in the study. These areas comprise only a small percentage of the total land area and few red pine plantations occur on them.

TABLE 4.--Distribution of study plots in relation to townships and geologic features

OTTAWA COUNTY

Townships in study units		Geologic feature		
		Dune sands	Lake sands	
			Well-drained	Imperfectly drained
		Number of plots		
I	Spring Lake, Crockery	4	3	2
II	Grand Haven, Robinson	2	3	1
III	Olive	2	5	2
IV	Port Sheldon	4	2	5
V	Park	1	1	2

WEXFORD COUNTY

Townships in study units		Geologic feature		
		Moraine	Outwash plain	Meltwater channel
		Number of plots		
I	Wexford, Springville	2	2	1
II	Slagle, Boon	5	4	1
III	South Branch, Henderson	2	2	0
IV	Selma, Cherry Grove	2	5	0

TABLE 5.--Location of the study plots[a]

OTTAWA COUNTY

Plot number	General land office description	Federal number or owner's name	Plot number	General land office description	Federal number or owner's name
1	T5N,R16W, NW¼NE¼, Sec. 3	LU 851	21	T8N,R16W, SE¼NW¼, Sec. 5	Mitchell
2	T5N,R16W, SE¼SE¼, Sec. 3	LU 745	22	T8N,R16W, SW¼NE¼, Sec.12	Johnson
3	T5N,R16W, SW¼SW¼, Sec.15	Crispel	23	T8N,R16W, NE¼NE¼, Sec.34	Kieft
4	T7N,R16W, SW¼SW¼, Sec.34	LU 540	24	T6N,R15W, NW¼SW¼, Sec. 9	LU 845
5	T6N,R16W, NW¼SE¼, Sec. 2	LU 595	25	T6N,R15W, SE¼SE¼, Sec. 8	LU 846
6	T6N,R16W, SE¼NE¼, Sec. 3	LU 600	26	T6N,R15W, SE¼NW¼, Sec. 6	LU 580
7	T6N,R16W, NW¼SE¼, Sec. 1	LU 586	27	T6N,R15W, NW¼NW¼, Sec. 8	LU 633
8	T6N,R16W, SW¼SW¼, Sec. 2	LU 858	28	T6N,R15W, NW¼SE¼, Sec. 4	LU 554
9	T6N,R16W, SW¼NE¼, Sec.34	LU 820	29	T6N,R15W, SE¼SE¼, Sec. 6	LU 583
10	T6N,R16W, SE¼SW¼, Sec.34	LU 721	30	T6N,R16W, SE¼NE¼, Sec. 3	LU 600
11	T7N,R16W, SE¼SW¼, Sec.34	LU 540	31	T6N,R16W, SW¼SW¼, Sec. 2	LU 858
12	T7N,R16W, NE¼NE¼, Sec.34	Winters	32	T6N,R16W, SW¼NE¼, Sec.28	LU 714
13	T7N,R16W, SE¼SW¼, Sec.33	Donahue	33	T6N,R16W, SW¼NE¼, Sec.28	LU 714
14	T7N,R16W, SE¼SW¼, Sec.34	LU 540	34	T6N,R16W, SW¼SE¼, Sec.35	LU 730
15	T7N,R16W, SW¼NW¼, Sec.34	Sheehan	35	T6N,R15W, SW¼SW¼, Sec. 9	LU 646
16	T7N,R16W, SE¼SW¼, Sec.26	Agnew	36	T6N,R15W, NE¼NE¼, Sec.18	Nienhuis
17	T7N,R16W, NE¼SW¼, Sec.33	Donahue	37	T6N,R15W, SW¼SW¼, Sec.20	Hoffman
18	T7N,R16W, NE¼SW¼, Sec.36	Biehle	38	T5N,R16W, SE¼SE¼, Sec.16	Ott. Co. 38
19	T8N,R16W, SW¼SW¼, Sec. 3	DeWitt	39	T7N,R15W, NE¼SE¼, Sec. 2	Ott. Co. 406
20	T8N,R16W, SE¼SE¼, Sec. 5	Nienhuis			

[a]The descriptions and titles were obtained from: Farm plat book, 1960. Ottawa Co., Mich., and files of the West Ottawa Soil Conservation District, Grand Haven, Mich.

TABLE 5.--Continued[a]

WEXFORD COUNTY

Plot number	General land office description	Federal number or owner's name	Plot number	General land office description	Federal number or owner's name
40	T22N,R12W, SE¼SE¼, Sec.11	P-48 bo	53	T21N,R12W, NE¼SE¼, Sec.12	P-47 bl
41	T22N,R11W, SW¼NW¼, Sec.16	P-37 bl	54	T22N,R12W, SE¼NE¼, Sec. 7	P-23 A
42	T22N,R11W, NW¼NE¼, Sec.21	P-37 bl	55	T23N,R12W, NW¼SW¼, Sec.29	P-28 A
43	T21N,R10W, SW¼NE¼, Sec.10	P-41 bo	56	T22N,R10W, SE¼NE¼, Sec. 2	P-50 bl
44	T21N,R11W, SW¼SE¼, Sec.12	P-58 bl	57	T22N,R10W, NW¼SW¼, Sec. 1	P-50 bl
45	T22N,R12W, NE¼SW¼, Sec.29	P-52 bo	58	T22N,R11W, SW¼NE¼, Sec. 2	P-45 b2
46	T22N,R12W, SW¼NW¼, Sec.28	P-25 c	59	T22N,R11W, SW¼NE¼, Sec. 2	P-45 b2
47	T23N,R12W, SW¼SW¼, Sec.34	P-44 b2	60	T22N,R11W, SE¼SW¼, Sec.23	P-46 bl
48	T23N,R12W, SE¼SE¼, Sec.26	P-44 bl	61	T22N,R10W, SE¼SW¼, Sec.15	P-40 bl
49	T23N,R12W, NE¼SW¼, Sec.27	P-44 b2	62	T22N,R10W, NE¼SE¼, Sec. 2	Billett
50	T24N,R12W, NE¼SW¼, Sec.31	Michigan	63	T22N,R10W, NW¼SW¼, Sec. 4	P-50 bl
51	T21N,R11W, NW¼NW¼, Sec. 2	P-43 b2	64	T22N,R10W, NW¼SW¼, Sec. 4	P-50 bl
52	T21N,R11W, NE¼NW¼, Sec. 4	P-28 A	65	T22N,R11W, SE¼SW¼, Sec.16	Hilton

[a]The descriptions and titles were obtained from: Farm plat book. 1956, Wexford Co., Mich., and the files of the Lower Michigan National Forest, Cadillac, Mich.

TABLE 6.--The mean annual periodic height growth of the sampled red pine growing on each plot
Based on a ten-tree sample per plot

OTTAWA COUNTY

Plot number	1939	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960
											--Inches--											
1	--	--	--	--	--	--	--	--	--	--	1.6	3.5	5.5	7.6	9.2	9.3	6.6	7.4	4.2	5.7	8.7	15.8
2	--	--	--	--	--	--	--	--	--	--	--	4.1	3.8	6.1	6.3	4.3	4.2	2.4	1.6	5.6	13.5	15.4
3	--	--	--	--	--	--	--	--	--	--	3.0	5.7	7.1	8.7	9.3	9.3	8.1	6.1	6.3	12.5	12.5	16.2
4	--	--	--	--	--	--	--	--	3.5	4.4	5.5	7.3	10.9	14.1	16.0	17.3	16.9	13.3	10.0	9.1	15.2	15.9
5	--	--	--	--	--	3.4	3.1	5.0	5.8	6.0	7.5	8.9	12.6	11.8	15.3	16.5	17.0	12.9	11.6	14.1	13.8	14.1
6	--	--	--	--	--	--	--	--	--	--	--	2.0	4.4	4.5	5.0	7.7	8.4	3.5	4.4	3.9	13.9	20.0
7	--	--	--	--	--	--	--	--	--	--	--	--	3.0	5.1	6.2	8.6	5.2	11.6	10.1	12.0	16.9	18.7
8	--	--	--	--	--	--	--	--	--	--	--	2.3	3.4	6.3	7.2	8.6	8.9	9.6	4.6	9.9	13.4	19.3
9	--	--	--	--	--	--	--	--	--	--	--	--	--	--	3.7	7.3	8.5	8.3	5.6	9.5	16.6	19.6
10	--	--	--	--	--	--	--	--	--	--	--	--	--	3.1	5.9	7.5	7.7	8.1	7.4	9.9	15.7	16.2
11	--	--	--	--	--	--	--	--	--	--	--	3.6	6.6	7.6	9.7	11.7	13.3	11.2	7.9	9.2	19.1	24.4
12	--	--	--	--	--	--	--	--	--	--	3.5	5.7	8.7	8.7	11.5	13.1	13.5	12.1	13.4	19.0	18.5	21.3
13	--	--	--	--	--	--	--	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
14	--	--	--	--	--	--	--	--	--	--	--	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
15	--	--	--	--	--	--	--	3.7	6.9	8.5	10.3	10.7	16.8	17.6	16.8	17.1	18.5	16.2	16.9	18.7	17.9	19.1
16	--	--	--	--	--	--	3.0	6.4	6.5	11.3	8.2	13.0	17.9	17.3	17.7	16.9	17.8	12.8	20.3	16.1	18.9	20.1
17	--	--	--	--	--	4.3	4.2	5.4	6.1	5.9	4.9	4.5	5.0	6.8	8.8	10.4	14.5	10.6	9.9	11.9	14.4	14.7
18	--	--	--	--	--	--	4.4	4.7	5.6	6.1	8.4	7.8	9.7	12.8	14.6	16.3	15.5	10.7	12.1	11.5	16.0	23.6
19	--	--	--	2.9	4.0	6.5	8.3	9.6	11.0	10.9	9.9	12.0	14.9	13.9	18.6	16.8	21.1	16.9	15.9	13.6	17.3	20.2
20	--	--	--	--	--	2.5	3.7	4.9	5.7	7.6	9.2	9.8	10.9	9.8	11.2	11.9	9.7	8.6	8.1	6.9	14.0	21.3
21	--	--	--	3.0	5.1	4.8	6.9	8.7	9.6	10.5	9.2	12.5	19.2	15.2	20.5	14.7	18.5	18.3	16.7	15.9	17.5	21.4
22	--	--	--	--	--	--	--	--	--	--	--	4.0	6.4	9.7	11.0	13.1	17.3	12.9	16.6	19.0	23.2	23.8
23	--	--	--	3.9	4.9	7.4	8.8	11.5	12.1	13.6	14.8	15.9	19.7	19.7	21.1	15.8	19.1	14.9	14.6	17.8	16.6	17.1
24	--	--	--	--	--	--	--	--	--	--	--	--	2.8	5.6	10.0	10.7	11.0	10.4	10.2	9.5	23.1	29.3
25	--	--	--	--	--	--	--	--	--	--	--	--	3.1	4.9	9.4	11.7	9.2	7.5	4.2	13.5	21.8	23.4
26	--	--	--	--	--	--	--	--	--	--	--	--	--	4.4	9.2	10.8	13.3	14.7	19.8	21.7	24.3	27.1
27	--	--	--	--	--	--	--	--	--	--	--	--	--	3.9	9.8	10.4	11.8	14.5	20.0	16.7	20.0	26.1
28	--	--	--	3.0	4.6	8.0	6.9	9.1	7.9	10.7	10.3	14.2	20.1	20.8	22.6	24.5	22.8	17.9	20.6	21.4	23.6	22.1
29	--	2.3	4.3	7.4	9.9	12.1	13.3	17.3	17.9	20.5	18.3	17.6	22.8	22.3	22.8	23.0	24.6	23.3	23.1	22.8	20.0	20.6
30	--	--	--	--	--	--	--	--	--	--	--	4.6	9.0	10.3	10.8	13.4	17.3	18.6	16.5	13.1	19.5	25.4
31	--	--	--	--	--	--	--	--	--	--	--	3.4	5.4	7.6	10.9	12.9	17.4	18.5	17.5	14.1	20.5	25.0
32	--	--	--	--	--	--	--	--	--	--	--	--	3.7	7.6	10.0	8.5	13.1	12.0	13.9	16.4	13.3	18.0
33	--	--	--	--	--	--	--	--	--	--	--	--	1.1	2.3	2.7	5.4	5.1	5.7	3.3	5.6	7.1	7.0
34	--	--	--	--	--	--	--	--	--	--	--	--	--	--	3.2	5.9	7.7	8.8	6.7	7.1	13.0	20.6
35	--	--	--	--	--	--	--	2.8	4.1	6.3	6.3	10.7	15.7	18.1	21.8	20.9	23.3	18.4	11.7	17.1	21.6	20.4
36	--	--	--	--	--	--	--	--	--	--	--	--	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2	2.2
37	--	--	--	--	--	--	3.3	6.2	7.8	6.9	10.0	10.8	15.4	16.9	20.8	18.7	16.0	12.4	9.3	14.8	17.5	15.7
38	--	--	--	--	--	--	2.4	4.9	6.3	9.0	9.5	14.0	17.4	18.8	19.9	17.2	17.3	14.2	12.3	18.3	16.2	18.3
39	--	--	3.2	4.8	6.7	9.0	9.6	14.4	15.8	20.0	15.2	22.3	22.4	22.4	27.3	22.8	23.9	25.8	25.9	24.5	26.7	25.6

TABLE 6.--Continued

WEXFORD COUNTY

Plot number	1939	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960
											--Inches--											
40	--	--	--	--	--	--	--	--	--	--	--	--	--	2.4	5.9	11.2	12.3	16.3	21.0	21.9	24.6	29.8
41	--	--	--	--	--	--	--	--	2.7	4.9	7.3	10.6	11.8	13.1	20.9	26.3	18.4	24.2	25.8	20.1	22.6	27.0
42	--	--	--	--	--	--	--	--	--	3.8	5.6	8.2	10.8	11.7	16.6	23.0	19.2	19.5	22.8	23.1	22.6	25.0
43	--	--	--	--	--	--	--	--	--	--	2.9	4.6	7.9	10.8	15.3	20.4	21.1	27.0	29.0	25.4	28.2	29.2
44	--	--	--	--	--	--	--	--	--	--	--	--	3.7	6.7	10.5	15.1	16.8	21.1	23.9	23.1	23.0	27.6
45	--	--	--	--	--	--	--	--	--	--	--	--	--	--	3.4	6.0	8.4	11.5	16.0	14.2	22.0	25.7
46	--	.3	1.5	2.7	4.1	5.3	7.0	9.2	12.5	13.9	16.1	16.9	18.0	17.4	20.6	18.4	17.6	16.2	11.0	15.4	18.0	19.6
47	--	--	--	--	--	--	--	--	--	--	--	4.3	6.5	8.0	9.6	12.0	12.8	16.5	21.6	17.2	22.9	30.5
48	--	--	--	--	--	--	--	--	--	--	--	3.7	5.0	9.0	14.8	17.5	17.0	23.1	29.7	26.5	28.6	31.8
49	--	--	--	--	--	--	--	--	--	--	--	3.9	5.5	8.3	9.8	11.9	12.8	13.2	14.4	14.3	19.8	20.6
50	--	--	--	--	--	--	--	--	--	--	--	--	2.5	5.6	11.2	12.2	13.8	18.6	24.2	18.6	18.5	26.6
51	--	--	--	--	--	--	--	--	--	--	--	3.2	5.4	8.9	11.9	16.5	17.3	19.3	21.9	20.8	17.6	20.9
52	--	--	--	2.4	4.7	7.6	7.7	13.9	13.2	15.4	14.0	12.9	12.5	14.3	18.1	17.9	16.2	19.1	22.2	17.7	15.6	19.0
53	--	--	--	--	--	--	--	--	--	--	--	--	--	3.3	7.5	10.4	9.6	13.4	16.9	15.5	20.7	28.5
54	1.7	2.6	7.5	7.3	9.7	10.3	8.5	11.6	10.0	9.8	9.2	15.5	14.5	18.7	24.4	24.0	13.8	15.8	21.2	16.6	21.4	20.9
55	3.7	5.4	5.4	5.8	8.9	11.6	10.2	12.8	12.8	12.6	11.3	14.6	17.4	16.4	20.8	19.4	17.4	19.6	22.2	20.6	21.8	21.5
56	--	--	--	--	--	--	--	--	--	--	--	--	--	3.1	4.3	6.9	9.0	13.5	19.1	23.3	24.7	27.3
57	--	--	--	--	--	--	--	--	--	--	--	--	--	2.1	3.3	7.6	9.5	12.7	19.3	22.5	25.5	28.9
58	--	--	--	--	--	--	--	--	--	--	--	--	3.2	3.5	4.3	5.7	7.7	7.6	2.8	13.6	15.5	2.9
59	--	--	--	--	--	--	--	--	--	--	--	--	5.4	4.8	10.3	12.4	14.2	17.8	22.1	20.7	24.6	28.3
60	--	--	--	--	--	--	--	--	--	--	--	--	4.0	6.8	9.3	11.1	11.8	12.7	21.0	22.8	22.3	28.6
61	--	--	--	--	--	--	--	--	--	--	1.8	4.6	7.5	9.0	13.0	17.0	14.6	18.2	21.6	19.8	21.3	27.8
62	--	--	--	--	--	--	--	--	--	--	--	--	--	--	2.7	2.7	2.7	2.7	2.7	2.7	2.7	2.7
63	--	--	--	--	--	--	--	--	--	--	--	--	--	2.8	4.7	7.5	9.2	10.4	13.4	19.8	21.8	27.1
64	--	--	--	--	--	--	--	--	--	--	--	--	--	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5
65	--	--	--	--	--	--	--	--	--	--	--	--	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8	2.8

TABLE 7.--The mean diameters (o.b.) of red pine growing on the study plots. Based on a ten-tree sample per plot

OTTAWA COUNTY

Plot number	Diameter D.b.h.	Diameter One foot	Plot number	Diameter D.b.h.	Diameter One foot	Plot number	Diameter D.b.h.	Diameter One foot
	Inches			Inches			Inches	
1	.9	2.5	14	0	.5	27	2.3	3.3
2	.7	2.3	15	3.9	4.9	28	4.0	4.6
3	1.8	4.0	16	3.6	4.5	29	8.5	10.0
4	3.8	5.3	17	2.6	4.2	30	3.0	4.0
5	3.4	4.9	18	4.3	5.5	31	2.8	3.9
6	.6	2.2	19	4.0	4.8	32	2.1	3.2
7	1.2	2.8	20	3.9	5.2	33	0	1.1
8	1.3	2.7	21	3.9	4.6	34	.6	1.7
9	.8	2.0	22	3.0	4.5	35	4.6	5.8
10	.8	2.0	23	5.3	6.2	36	0	.5
11	1.9	3.3	24	1.6	2.8	37	4.7	5.9
12	2.3	3.2	25	1.6	3.0	38	4.3	5.3
13	0	.5	26	2.4	3.2	39	5.9	7.0

WEXFORD COUNTY

40	2.1	3.0	49	2.2	3.6	58	.6	.2
41	4.3	5.3	50	2.5	3.6	59	2.6	3.7
42	3.7	4.6	51	2.9	4.0	60	2.4	3.4
43	3.6	4.3	52	4.6	5.2	61	2.9	3.8
44	2.8	3.8	53	2.1	3.1	62	0	.5
45	1.5	2.5	54	4.7	5.5	63	1.8	2.9
46	5.6	6.7	55	4.7	5.5	64	0	.5
47	2.9	3.8	56	2.1	3.1	65	0	.5
48	3.5	4.3	57	2.1	3.1			

TABLE 8.--Rooting characteristics of a selected red pine from each plot

OTTAWA COUNTY

Plot number	Maximum depth of roots	Depth of tap root	Approximate depth of majority of roots	Plot number	Maximum depth of roots	Depth of tap root	Approximate depth of majority of roots
	--Inches--				--Inches--		
1	40	--[a]	18	21	72	60	72
2	15	15[b]	15	22	60	--	48
3	72	72	60	23	84	48	72
4	72	72	36	24	84	60	48
5	72	48	72	25	60	48	24
6	24	24[b]	12	26	30	30	18
7	72	72	48	27	48	42	30
8	22	22	12	28	66	30	42
9	30	30	10	29	84	54	54
10	14	14	12	30	66	60	48
11	60	30	24	31	66	48	48
12	24	12	20	32	60	42[b]	n.r.[c]
13	12	--	6	33	24	--	6
14	12	--	12	34	36	--	12
15	84	40	72	35	72	60	40
16	84	48	72	36	12	--[b]	12
17	72	72	n.r.[c]	37	30	26	18
18	18	--	18	38	60	48	48
19	72	60	60	39	120	46	60
20	22	22	22				

[a]Tap root did not develop

[b]Tap root poorly developed

[c]Data not recorded

TABLE 8.--Continued

WEXFORD COUNTY

Plot number	Maximum depth of roots	Depth of tap root	Approximate depth of majority of roots	Plot number	Maximum depth of roots	Depth of tap root	Approximate depth of majority of roots
	--Inches--				--Inches--		
40	108	30[b]	24	53	60	n.r.[c]	24
41	100	n.r.[c]	30	54	84	45	30
42	80	50	30	55	72	36	36
43	50	36	36	56	60	36[b]	48
44	94	--[a]	24	57	54	28[b]	24
45	36	24[b]	20	58	36	30	20
46	60	54	24	59	66	46	20
47	52	40	24	60	78	36[b]	36
48	72	--	30	61	76	40[d]	30
49	56	45[b]	40	62	12	--	12
50	72	33[b]	36	63	36	24	24
51	72	36	36	64	10	--	10
52	96	36[b]	36	65	12	--	10

[a]Tap root did not develop.

[b]Tap root poorly developed.

[c]Data not recorded.

[d]Forked.

TABLE 9.--The mean annual number of branches per whorl of sampled red pine
Based on a ten-tree sample per plot

OTTAWA COUNTY

Plot number	1939	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959
											--Number--										
1	--	--	--	--	--	--	--	--	--	--	2.1	2.0	2.8	3.0	3.5	2.5	1.6	.7	1.1	1.3	2.6
2	--	--	--	--	--	--	--	--	--	--	--	1.5	1.8	2.6	1.7	.7	.9	.4	.9	2.8	4.1
3	--	--	--	--	--	--	--	--	--	--	1.5	3.0	3.7	2.6	1.6	2.2	.8	.7	1.4	2.7	2.5
4	--	--	--	--	--	--	--	--	2.1	2.1	2.3	2.9	4.3	4.6	4.5	4.9	2.6	1.4	.6	1.8	2.1
5	--	--	--	--	--	1.8	2.0	2.4	3.2	2.5	3.2	2.0	3.0	2.8	3.8	3.7	3.3	1.1	1.4	1.5	1.5
6	--	--	--	--	--	--	--	--	--	--	--	.8	1.8	2.5	2.2	2.6	1.0	.1	.6	3.3	3.5
7	--	--	--	--	--	--	--	--	--	--	--	--	1.7	1.7	2.3	1.5	2.0	2.3	1.4	3.3	4.3
8	--	--	--	--	--	--	--	--	--	--	--	1.7	2.6	2.6	3.2	2.7	1.8	.3	1.9	4.2	4.7
9	--	--	--	--	--	--	--	--	--	--	--	--	--	--	1.6	2.5	2.6	2.3	.7	2.4	2.8
10	--	--	--	--	--	--	--	--	--	--	--	--	--	1.5	2.6	3.9	3.2	1.9	1.8	4.2	3.0
11	--	--	--	--	--	--	--	--	--	--	--	2.4	2.7	3.8	4.6	4.1	3.2	1.2	.5	2.3	4.8
12	--	--	--	--	--	--	--	--	--	--	1.7	2.6	3.3	4.0	4.4	3.9	1.6	1.0	2.8	4.7	4.5
13	--	--	--	--	--	--	--	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14	--	--	--	--	--	--	--	--	--	--	--	0	0	0	0	0	0	0	0	0	0
15	--	--	--	--	--	--	--	2.3	2.8	3.1	2.7	3.7	3.1	3.6	2.7	2.9	2.3	1.3	2.9	2.6	1.7
16	--	--	--	--	--	--	1.4	2.6	2.3	4.3	4.3	5.1	5.8	4.5	4.3	3.2	2.1	2.4	2.8	4.0	3.7
17	--	--	--	--	--	1.6	2.2	2.3	2.8	3.4	2.0	1.6	1.8	2.0	1.6	2.7	2.4	1.1	2.2	3.3	3.5
18	--	--	--	--	--	--	1.9	2.4	3.1	3.4	2.8	3.6	3.5	4.6	4.7	4.6	1.4	1.1	.5	1.8	3.6
19	--	--	--	1.9	2.8	3.8	3.7	4.5	4.2	2.9	3.4	2.5	2.5	4.1	3.3	2.9	1.7	1.9	2.3	3.4	4.0
20	--	--	--	--	--	1.6	2.2	2.4	3.6	3.9	4.1	4.9	4.1	2.5	2.3	1.4	1.5	.8	.8	2.0	3.1
21	--	--	--	2.3	2.5	3.0	3.5	3.9	2.8	3.8	2.2	2.4	2.2	3.7	3.3	2.7	4.1	3.0	4.2	3.8	3.9
22	--	--	--	--	--	--	--	--	--	--	--	2.0	3.1	4.2	3.5	4.0	2.6	1.4	1.8	2.3	4.6
23	--	--	--	2.1	2.6	3.3	3.8	4.8	4.4	4.4	4.6	4.5	4.6	4.1	3.6	1.8	2.5	1.4	3.6	4.1	2.0
24	--	--	--	--	--	--	--	--	--	--	--	--	1.9	2.4	2.5	2.6	1.8	1.6	.9	2.3	3.3
25	--	--	--	--	--	--	--	--	--	--	--	--	1.2	2.4	3.6	2.6	1.2	.6	1.6	1.9	3.7
26	--	--	--	--	--	--	--	--	--	--	--	--	--	2.3	4.3	3.7	3.5	3.9	5.5	5.7	5.2
27	--	--	--	--	--	--	--	--	--	--	--	--	--	2.5	4.6	3.7	5.1	3.6	3.9	4.5	3.7
28	--	--	--	1.5	2.4	3.2	3.2	4.2	3.4	3.8	3.8	4.8	6.1	4.7	5.4	5.1	4.5	3.3	4.2	4.1	4.2
29	--	1.3	1.9	2.9	4.1	5.0	5.4	4.9	5.2	5.4	4.1	4.3	5.7	5.8	5.2	5.8	5.7	4.7	5.1	3.2	3.0
30	--	--	--	--	--	--	--	--	--	--	--	2.3	4.7	4.2	4.5	5.1	5.1	3.7	2.6	3.6	4.1
31	--	--	--	--	--	--	--	--	--	--	--	1.6	2.9	3.3	4.0	4.7	5.3	4.4	1.7	3.0	3.8
32	--	--	--	--	--	--	--	--	--	--	--	--	1.8	3.0	3.2	3.5	4.0	3.7	3.0	1.9	3.8
33	--	--	--	--	--	--	--	--	--	--	--	--	1.3	1.8	1.8	1.4	1.3	1.3	.9	1.3	1.7
34	--	--	--	--	--	--	--	--	--	--	--	--	--	--	1.3	2.4	3.1	1.7	1.9	2.3	3.2
35	--	--	--	--	--	--	--	1.9	2.0	2.8	3.5	4.6	5.5	5.7	4.6	4.3	2.5	.7	2.3	2.6	2.5
36	--	--	--	--	--	--	--	--	--	--	--	--	0	0	0	0	0	0	0	0	0
37	--	--	--	--	--	--	1.1	2.0	2.9	3.1	3.7	4.3	3.7	4.5	3.4	2.0	1.6	1.2	1.8	2.5	1.2
38	--	--	--	--	--	--	1.2	2.4	2.4	3.5	4.2	4.4	4.3	4.1	2.2	1.3	1.7	1.4	4.1	3.8	2.9
39	--	--	1.8	3.0	3.8	4.2	4.3	5.1	4.7	5.4	4.9	5.2	5.8	5.7	4.8	4.8	4.9	3.9	3.0	5.8	5.6

TABLE 9.--Continued

WEXFORD COUNTY

Plot number	1939	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959
	--Number--																				
40	--	--	--	--	--	--	--	--	--	--	--	--	--	2.2	3.9	3.9	4.5	3.9	4.7	6.0	6.6
41	--	--	--	--	--	--	--	--	2.4	2.7	3.3	4.0	5.0	5.6	6.1	7.0	7.1	5.6	6.3	6.4	5.7
42	--	--	--	--	--	--	--	--	--	1.7	2.4	4.5	4.4	5.1	6.0	6.3	6.1	5.3	7.1	6.3	5.4
43	--	--	--	--	--	--	--	--	--	--	1.7	2.8	4.2	5.7	5.5	6.1	5.7	5.8	6.9	6.5	6.7
44	--	--	--	--	--	--	--	--	--	--	--	--	2.2	4.2	3.7	5.5	5.3	5.6	6.9	6.7	6.3
45	--	--	--	--	--	--	--	--	--	--	--	--	--	--	2.9	2.7	3.2	3.7	3.8	4.4	3.5
46	--	.4	1.5	2.1	2.5	3.2	3.5	4.1	4.1	3.3	4.5	3.1	2.9	3.4	1.3	2.0	.9	1.1	2.6	4.3	3.7
47	--	--	--	--	--	--	--	--	--	--	--	2.6	3.4	4.4	4.2	4.4	5.3	4.8	7.1	5.6	6.2
48	--	--	--	--	--	--	--	--	--	--	--	2.4	2.6	3.8	5.3	5.1	5.7	5.9	7.1	7.1	6.8
49	--	--	--	--	--	--	--	--	--	--	--	1.7	2.7	3.9	4.3	2.6	1.8	.6	2.2	3.7	1.6
50	--	--	--	--	--	--	--	--	--	--	--	--	2.0	3.5	4.9	4.6	5.4	4.9	6.9	5.8	5.3
51	--	--	--	--	--	--	--	--	--	--	--	2.9	3.4	5.1	5.0	6.0	6.3	5.3	7.0	6.1	6.2
52	--	--	--	3.0	3.1	3.0	4.1	5.3	4.9	4.6	5.0	4.3	4.9	5.2	5.1	4.9	5.2	4.8	6.0	5.3	4.9
53	--	--	--	--	--	--	--	--	--	--	--	--	--	2.0	2.9	3.3	4.3	4.6	6.0	6.0	5.7
54	1.3	1.8	3.5	2.6	3.3	3.3	3.6	3.8	3.2	2.7	3.3	3.8	4.5	5.0	5.9	5.4	2.6	3.8	5.5	4.6	5.5
55	1.6	1.6	2.6	2.8	2.9	3.7	4.5	4.9	4.6	4.0	4.8	4.4	4.6	5.0	4.8	3.8	4.5	4.2	5.0	4.6	4.9
56	--	--	--	--	--	--	--	--	--	--	--	--	--	2.1	3.0	3.6	4.0	4.5	4.9	4.9	4.3
57	--	--	--	--	--	--	--	--	--	--	--	--	--	1.4	4.1	4.3	4.4	4.0	5.1	6.3	5.8
58	--	--	--	--	--	--	--	--	--	--	--	--	1.9	1.8	2.4	2.3	2.9	.5	1.8	4.3	.3
59	--	--	--	--	--	--	--	--	--	--	--	--	3.5	3.6	4.3	4.7	4.2	4.1	6.0	6.2	5.4
60	--	--	--	--	--	--	--	--	--	--	--	--	2.6	3.5	4.3	5.3	5.4	4.1	5.7	7.1	6.8
61	--	--	--	--	--	--	--	--	--	--	1.5	2.8	3.8	4.3	4.9	5.0	5.0	5.2	6.3	6.0	5.1
62	--	--	--	--	--	--	--	--	--	--	--	--	0	0	0	0	0	0	0	0	0
63	--	--	--	--	--	--	--	--	--	--	--	--	--	1.7	3.4	3.1	3.6	2.0	3.7	3.8	4.8
64	--	--	--	--	--	--	--	--	--	--	--	--	--	0	0	0	0	0	0	0	0
65	--	--	--	--	--	--	--	--	--	--	--	--	0	0	0	0	0	0	0	0	0

TABLE 10.--The annual percentage of sampled red pine trees showing forking of the main stem
Based on a ten-tree sample per plot

OTTAWA COUNTY

Plot number	1939	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959
	--percent--																				
1	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	--	--	--	--	--	--
2	--	--	--	--	--	--	--	--	--	--	--	--	10	--	30	10	--	--	--	10	10
3	--	--	--	--	--	--	--	--	--	--	--	--	10	20	--	20	20	--	10	10	20
4	--	--	--	--	--	--	--	--	--	--	--	--	--	10	--	20	--	--	20	10	--
5	--	--	--	--	--	--	--	--	--	--	10	10	10	--	--	--	--	10	30	20	30
6	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	10	--	--	10	50
7	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	--	10	20	30	20	10
8	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	--	--	--	--	10	--
9	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	10	10	40
10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	10	10	--
11	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	--	--	20	--	--	--
12	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	10	--	10	20	--
13	--	--	--	--	--	--	--	10	10	10	10	10	10	10	10	10	10	10	10	10	10
14	--	--	--	--	--	--	--	--	--	--	--	10	10	10	10	10	10	10	10	10	10
15	--	--	--	--	--	--	--	--	--	--	--	--	10	--	10	--	--	30	--	20	10
16	--	--	--	--	--	--	--	--	--	--	--	--	--	10	--	--	--	20	--	10	--
17	--	--	--	--	--	--	--	--	10	10	10	20	--	10	10	--	--	10	10	20	--
18	--	--	--	--	--	--	--	--	--	--	10	10	--	--	10	--	--	--	10	10	--
19	--	--	--	--	--	--	--	--	--	--	--	20	10	10	10	--	--	10	10	20	--
20	--	--	--	--	--	--	--	--	--	--	--	--	--	10	--	20	30	20	10	--	--
21	--	--	--	--	--	--	--	--	10	--	30	--	10	10	10	10	--	10	10	--	--
22	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	20	40	40	10
23	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	10	10	10	--	--
24	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	--	20	10	20	30
25	--	--	--	--	--	--	--	--	--	--	--	--	--	--	20	10	10	--	20	40	40
26	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	--
27	--	--	--	--	--	--	--	--	--	--	--	--	--	--	20	10	--	10	--	20	10
28	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
29	--	--	--	--	10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	--
30	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	20	20	10
31	--	--	--	--	--	--	--	--	--	--	--	--	--	20	10	--	--	10	20	10	10
32	--	--	--	--	--	--	--	--	--	--	--	--	--	20	10	--	--	10	20	40	10
33	--	--	--	--	--	--	--	--	--	--	--	--	--	10	30	60	40	10	10	10	--
34	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	10	20	10	20	10
35	--	--	--	--	--	--	--	--	--	--	--	--	--	10	10	--	10	--	10	10	--
36	--	--	--	--	--	--	--	--	--	--	--	--	10	10	10	10	10	10	10	10	10
37	--	--	--	--	--	--	--	--	--	--	--	--	10	10	20	10	10	10	--	10	20
38	--	--	--	--	--	--	--	--	--	--	--	--	--	60	30	40	10	30	--	--	--
39	--	--	--	--	--	10	--	--	--	--	--	10	--	--	10	--	--	20	10	--	--

TABLE 10.--Continued

WEXFORD COUNTY

Plot number	1939	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959
	--Percent--																				
40	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	20	--	--	--
41	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	--	--
42	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	20	--
43	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
44	--	--	--	--	--	--	--	--	--	--	--	--	--	10	--	--	--	--	--	--	--
45	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	10	10	20	60
46	--	--	--	10	--	--	--	--	20	--	20	10	10	10	40	10	10	10	30	--	10
47	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
48	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
49	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	--	30	30	30	20	--
50	--	--	--	--	--	--	--	--	--	--	--	--	10	10	--	10	--	--	--	--	--
51	--	--	--	--	--	--	--	--	--	--	--	--	--	20	--	--	--	--	--	--	--
52	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
53	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10
54	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	40	10	--	--	--
55	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	--	--	--	--
56	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	20
57	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	20	--	--
58	--	--	--	--	--	--	--	--	--	--	--	--	10	--	--	10	10	10	20	--	--
59	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	10	10	--	10
60	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
61	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
62	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	10	10	10	10	10	10
63	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	10	10	10
64	--	--	--	--	--	--	--	--	--	--	--	--	--	10	10	10	10	10	10	10	10
65	--	--	--	--	--	--	--	--	--	--	--	--	10	10	10	10	10	10	10	10	10

TABLE 11.--The annual percentage of sampled red pine trees with bushes, posthorns and spikes
Based on a ten-tree sample per plot

OTTAWA COUNTY

Plot number	1939	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959
	--Percent--																				
1	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	20	30	40	40	--	10
2	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	20	50	60	50	10	--
3	--	--	--	--	--	--	--	--	--	--	--	--	--	10	--	60	60	50	50	10	--
4	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	10	20	30	20	10
5	--	--	--	--	--	--	--	--	--	--	--	10	10	--	10	10	--	20	10	10	--
6	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	10	50	30	70	10	--
7	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	20	20	10	40	10	--
8	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	10	40	70	50	--	--
9	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	50	--	30	20	--
10	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	30	--	--
11	--	--	--	--	--	--	--	--	--	--	--	--	--	10	--	--	40	40	40	30	--
12	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	20	30	20	--	--
13	--	--	--	--	--	--	--	10	10	10	10	10	10	10	10	10	10	10	10	10	--
14	--	--	--	--	--	--	--	--	--	--	--	10	10	10	10	10	10	10	10	10	--
15	--	--	--	--	--	--	--	--	--	10	10	10	10	20	--	20	50	20	--	--	--
16	--	--	--	--	--	--	--	--	--	20	--	--	--	--	--	10	10	--	10	--	--
17	--	--	--	--	--	--	--	--	--	--	--	10	30	20	10	--	--	10	10	10	--
18	--	--	--	--	--	--	--	--	--	--	10	30	--	--	--	--	30	20	40	50	--
19	--	--	--	--	--	--	--	--	--	--	--	--	10	30	--	--	--	30	10	--	--
20	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	30	10	30	40	20	--
21	--	--	--	--	--	--	--	--	--	--	--	--	20	10	--	--	10	--	--	10	--
22	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	30	30	--	--
23	--	--	--	--	--	--	--	--	--	20	--	--	--	--	--	20	--	20	--	--	--
24	--	--	--	--	--	--	--	--	--	--	--	--	--	--	20	20	30	10	30	40	--
25	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	40	30	80	20	--	--
26	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	10	10	--	--	--
27	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	--	--	10	--	--
28	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	--	--	--
29	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	--	--	--
30	--	--	--	--	--	--	--	--	--	--	--	--	--	10	--	--	--	--	10	--	--
31	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	30	--	--
32	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	--	20	--	10	10
33	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	30	30	--	--
34	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	30	20	10	--
35	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	40	50	40	--	--
36	--	--	--	--	--	--	--	--	--	--	--	--	10	10	10	10	10	10	10	10	10
37	--	--	--	--	--	--	--	--	--	--	--	--	10	--	--	40	40	40	40	10	--
38	--	--	--	--	--	--	--	--	--	--	--	--	--	10	--	--	10	10	--	--	--
39	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	--	--	--

TABLE 11.--Continued

WEXFORD COUNTY

Plot number	1939	1940	1941	1942	1943	1944	1945	1946	1947	1948	1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959
	--Percent--																				
40	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
41	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
42	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
43	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
44	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
45	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
46	--	--	--	--	--	--	--	--	--	--	10	--	--	--	--	--	40	20	20	--	--
47	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
48	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
49	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	30	20	20	20	--	--
50	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
51	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
52	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
53	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
54	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	--	--	--
55	--	--	--	--	--	--	--	--	--	--	--	--	10	--	--	--	10	--	--	--	--
56	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
57	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
58	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	--	20	60	50	10
59	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	--	--	--
60	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
61	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
62	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	10	10	10	10	10
63	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	40	10	--
64	--	--	--	--	--	--	--	--	--	--	--	--	--	--	10	10	10	10	10	10	10
65	--	--	--	--	--	--	--	--	--	--	--	--	--	10	10	10	10	10	10	10	10

TABLE 12.--The mean internodal distance below a bush, posthorn or spike and the mean internodal distance of a lateral which replaced the injured leader[a]

Plot number	Number of takeovers			Mean internodal distance to bush			Mean internodal distance of takeover		
	one year	two years	more than two years	one year	two years	more than two years	one year	two years	more than two years
	-----Inches-----			-----Inches-----			-----Inches-----		
1	6	2	-	7.3	16.5	-	6.5	11.5	-
2	2	1	2	7.5	17.0	20.5	9.0	16.0	13.0
3	7	2	2	6.9	11.0	19.5	7.6	12.0	27.0
4	1	3	-	14.0	29.0	-	12.0	29.0	-
5	2	3	-	13.0	22.0	-	10.5	26.7	-
6	8	1	-	6.2	12.0	-	6.4	13.0	-
7	8	1	-	10.6	14.0	-	9.6	8.0	-
8	8	1	-	7.6	12.0	-	8.0	9.0	-
9	6	-	-	8.5	-	-	7.8	-	-
10	2	1	-	6.0	16.0	-	8.0	15.0	-
11	8	2	1	9.0	29.0	18.0	9.5	20.0	19.0
15	7	-	-	13.4	-	-	13.6	-	-
16	4	-	-	12.3	-	-	14.5	-	-
17	8	1	-	7.4	5.0	-	6.4	7.0	-
18	8	1	1	10.8	26.0	35.0	12.1	39.0	33.0
19	1	1	-	18.0	34.0	-	16.0	32.0	-
20	5	1	-	10.4	11.0	-	7.0	22.0	-
21	2	-	-	7.0	-	-	15.5	-	-

[a]The number of takeovers (lateral which replaced injured leader) differs from the number of all terminal injuries in Table 11. Only terminal damage resulting in takeover is considered in Table 12.

TABLE 12.--Continued

Plot number	Number of takeovers			Mean internodal distance to bush			Mean internodal distance of takeover		
	one year	two years	more than two years	one year	two years	more than two years	one year	two years	more than two years
	-----Inches-----			-----Inches-----			-----Inches-----		
22	5	-	-	13.6	-	-	12.5	-	-
23	4	-	-	14.0	-	-	13.3	-	-
24	8	-	-	10.0	-	-	10.1	-	-
25	5	-	-	8.8	-	-	9.2	-	-
26	2	-	-	13.0	-	-	9.5	-	-
27	1	-	-	18.0	-	-	23.0	-	-
29	2	-	-	12.0	-	-	14.0	-	-
31	2	-	-	21.0	-	-	16.0	-	-
32	4	-	-	12.5	-	-	12.8	-	-
33	1	-	-	8.0	-	-	6.0	-	-
34	3	-	-	10.7	-	-	10.3	-	-
35	4	-	-	13.0	-	-	12.5	-	-
37	4	-	-	21.8	-	-	18.3	-	-
39	1	-	-	24.0	-	-	24.0	-	-
46	3	1	-	19.3	26.0	-	15.7	29.0	-
49	4	1	-	10.5	23.0	-	11.5	25.0	-
54	1	-	-	14.0	-	-	11.0	-	-
58	3	1	4	6.0	14.0	19.5	4.7	12.0	22.8
63	2	1	-	11.0	17.0	-	11.0	17.0	-

TABLE 13.--The identification and description of the soil series for each study plot
Descriptions follow Soil Survey Staff (1951), Soil Survey Manual

Plot number	Soil series	Texture	Slope	Erosion	Horizons: Over-burden	A: Sub horizon	A: Depth	B: Sub horizon	B: Depth	A2Bt: Depth	Depth to textural differences: Hard pan	Cemented hard pan	Gravel bands	Textural bands	Mottling	Free water
		-------Class-------			-Inches-		-Inches-		--Inches--		----------Inches----------					
1	AuGres (--Saugatuck)	S	A	1	-	Ap	5	Bhir	7	-	5	-	-	-	-	46
2	AuGres (--Granby)	LS	A	1	-	Ap A2	8 3	Bh Bir	4 15	-	-	-	-	10	24	35
3	Rubicon	S	D	U	60	Ap	6	B22	6	-	-	-	-	72	-	-
4	Rubicon	S	B	2	-	Ap	6	B22 B3	14 6	-	-	-	-	72	-	-
5	Rubicon	S	C	2	-	Ap	6	B22 B3	14 6	-	-	-	-	72	-	-
6	AuGres (--Saugatuck)	S	A	1	-	Ap A2	5 3	Bir B2ir	5 17	-	-	-	-	-	-	36
7	Rubicon	S	D	U	24	Ap	6	B22	14	-	-	-	-	44	-	-
8	AuGres	S	A	1	-	A1 A2	4 2	Bhir Bir	3 9	-	-	-	-	-	-	42
9	AuGres (--Croswell)	S	A	1	-	A1 A2	2 7	Bir	10	-	24	-	-	-	-	60
10	Saugatuck (--Saugatuck)	S	A	1	-	Ap A2	9 3	Bhir	8	-	-	12	-	-	-	72
11	Rubicon	S	B	3	-	Ap	8	Bir B3	6 6	-	-	-	-	-	-	72
12	AuGres (--Saugatuck)	S	A	1	-	Ap	8	Bh Bir	4 6	-	12	-	-	-	-	36
13	Rubicon	S	C	U	-	eroded to "C" horizon										
14	Rubicon	S	C	U	-	eroded to "C" horizon										
15	Rubicon (--Grayling)	LS	A	2	-	Ap	8	Bir B3	7 11	-	-	-	84	42	-	-
16	Rubicon	S	C	3	12	A2	2	Bhir Bir	4 18	-	-	-	-	12	-	84
17	Rubicon	S	F	U	48	Ap	6	B2ir B3	14 4	-	-	-	-	48	-	-
18	Saugatuck (--AuGres)	S	A	1	-	Ap A2	8 2	B2h B2ir	6 22	-	-	22	-	-	-	72
19	Rubicon (--Croswell)	S	A	1	6	A1 A2	6 3	Bhir Bir B2ir	6 5 6	-	-	-	-	60	-	84
20	Saugatuck (--AuGres)	S	A	1	12	A2	3	Bh Bhir Bir	8 6 11	-	-	20	-	12	-	54
21	Rubicon (--Kalkaska)	S	C	[illegible]	[illegible]	A2	1	Bir B2ir	7 10	-	14	-	-	-	-	72
22	Rubicon	S	B	1	-	Ap	9	Bir B3	5 5	-	-	-	-	72	-	-

TABLE 13.--Continued

Plot number	Soil series	Texture	Slope	Erosion	Horizons						Depth to textural differences					
					Over-burden	A		B		A2Bt	Hard pan	Cemented hard pan	Gravel bands	Textural bands	Mottling	Free water
						Sub horizon	Depth	Sub horizon	Depth	Depth						
		Class			Inches		Inches		Inches		Inches					
23	Graycalm	LS	B	1	-	Ap	8	Bir B3	6 10	42	-	-	84	42	-	-
24	Rubicon	S	B	2	-	Al	2	Bir B3	12 6	-	-	-	-	108	-	-
25	Rubicon	S	B	3	4	Ap	9	Bir B2ir	6 9	-	-	-	-	66	-	-
26	Croswell	S	A	1	-	Ap	7	Bir B3	4 6	-	-	-	-	-	30	48
27	Rubicon (--Croswell)	S	B	2	-	Ap	7	Bhir Bir B3	3 3 12	-	-	-	-	-	-	54
28	Rubicon	S	B	2	-	Ap	6	Bir B3	8 20	-	-	-	52	-	-	-
29	Rubicon	S	C	3	40	-	-	Bir B2ir	4 4	-	-	-	-	40	-	84
30	Croswell	S	B	2	-	Ap	7	Bhir B3	6 18	-	-	-	-	42	-	72
31	Croswell (--Rubicon)	S	B	3	-	Ap	6	Bhir B3	6 18	-	-	-	-	36	-	72
32	Rubicon (--Graycalm)	S	B	2	-	Ap	3	Bhir Bir B2ir	4 4 9	-	-	-	42	66	-	-
33	Rubicon	S	B	2	-	Ap	9	Bir B2ir	6 9	-	-	-	-	-	-	-
34	AuGres (--Saugatuck)	S	A	1	-	Ap	8	Bh Bir B3	3 6 13	-	-	-	-	-	-	54
35	Rubicon	S	B	2	-	Ap	7	Bir B2ir	6 6	-	-	-	-	108	-	-
36	Rubicon	S	C	U	-	eroded to "C" horizon										
37	AuGres	S	A	1	-	Ap	8	Bh Bir B3	3 6 13	-	18	-	-	-	-	54
38	Rubicon (--Croswell)	S	B	2	-	Ap	6	Bir B2ir B3	6 16 6	-	-	-	-	96	-	-
39	Graycalm (--Karlin)	LS	B	2	-	Ap	12	Bir	6	18	-	-	108	60	-	-
40	Kalkaska	S	A	1	-	Ap	8	B2h B2ir	3 12	-	-	-	-	60	120	-
41	Kalkaska	S	A	1	-	Ap	7	B2h B2ir	4 11	-	-	-	-	96	-	-
42	Graycalm	S	B	1	-	Ap	8	Bhir B3	5 11	-	-	-	-	72	-	-

TABLE 13.--Continued

Plot number	Soil series	Texture	Slope	Erosion	Horizons: Over-burden	A: Sub horizon	A: Depth	B: Sub horizon	B: Depth	A2Bt: Depth	Depth to textural differences: Hard pan	Cemented hard pan	Gravel bands	Textural bands	Mottling	Free water
		-Class-			-Inches-		-Inches-		--Inches--		-Inches-					
43	Croswell	LS	A	1	-	A1	6	B2h	9	-	14	-	26	-	-	64
						A2	9	B2ir	22							
44	Kalkaska	LS	A	2	-	A2	4	B2h	7	-	-	-	110	60	-	-
								B2ir	13							
45	Kalkaska	S	A	2	-	A1	2	B2	2	-	-	-	-	-	-	-
						A2	3	B22	15							
46	Rubicon	S	C	2	-	A1	1	B2	5	-	-	-	-	72	-	-
						A2	3	B22	14							
47	Antrim	LS	A	1	-	Ap	4	B1r	5	-	-	-	15	-	-	60
								B2	3							
								B22	27							
48	Free Soil	LS	B	1	-	Ap	6	B1r	5	25	20	-	-	66	-	-
						A2	3	B2h	11							
49	Rubicon	LS	A	3	-	Ap	3	Bhir	27	-	-	-	-	62	-	-
						A2	5									
50	Kalkaska	S	A	1	-	A1	4	Bhir	13	-	-	-	84	40	-	-
						A2	3	B2ir	12							
51	Kalkaska	S	B	2	-	Ap	2	B2h	5	-	-	-	42	84	-	-
								B2ir	9							
52	Kalkaska	S	B	1	-	Ap	10	Bhir	16	-	16	-	60	-	-	-
53	Kalkaska (--Blue Lake)	LS	A	1	-	Ap	5	B2h	4	-	-	-	-	84	-	-
								B2ir	20							
54	Rubicon (--Grayling)	S	A	1	-	A1	3	Bhir	27	-	-	-	-	62	-	-
						A2	2									
55	Rubicon	S	A	1	-	A1	3	B2	3	-	-	-	32	84	-	-
						A2	3	B3	13							
56	Kalkaska	LS	A	1	-	Ap	8	B2h	6	-	-	-	78	30	-	-
								B2ir	16							
57	Kalkaska	LS	A	1	-	Ap	7	B2h	5	-	-	-	55	96	-	-
								B2ir	20							
58	East Lake	LS	B	1	-	Ap	8	Bh	31	-	-	-	48	-	-	-
						A2	4	Bhir	2							
59	East Lake	LS	B	1	-	Ap	8	B2	24	-	-	-	55	-	-	-
60	East Lake	LS	B	1	-	Ap	10	Bhir	8	-	-	-	20	72	-	-
								B3	28							
61	Kalkaska	S	A	1	-	Ap	6	B2h	4	-	30	-	-	96	-	108
								B2ir	22							
62	Blue Lake	S	C	U	-	Ap	7	B2h	6	-	-	-	-	40	-	-
								B2ir	18							
63	Graycalm	S	B	3	-	Ap	5	Bh	10	-	-	-	-	-	-	-
								B2h	21							
64	Kalkaska	S	B	7	-	eroded to "C" horizon										
65	Kalkaska	S	B	U	-	Ap	1	B2h	10	-	-	-	-	54	-	-
								B22	20							

TABLE 14.--Soil analysis of the plow zone from each study plot

OTTAWA COUNTY

Plot number	pH	Organic matter content	Major elements					Plot number	pH	Organic matter content	Major elements				
			N	P	K	C	Mg				N	P	K	C	Mg
	-Log.-	--%--	--Pounds per acre--						-Log.-	--%--	--Pounds per acre--				
1	4.8	2.2	-[a]	4	25	-	-	21	4.9	3.0	-	16	49	-	-
2	4.9	2.0	-	4	25	-	-	22	5.0	2.6	-	5	16	-	-
3	5.2	.8	-	4	34	-	-	23	5.0	1.5	-	5	30	-	T[b]
4	5.6	2.6	-	4	34	-	-	24	5.1	2.6	-	5	25	-	-
5	5.4	2.4	-	4	25	-	-	25	4.8	1.7	-	4	8	-	-
6	5.0	3.0	-	2	34	320	-	26	1.7	1.7	-	4	8	-	-
7	5.3	.7	-	3	20	-	-	27	2.8	2.8	-	4	16	-	-
8	4.8	3.6	-	1	12	-	-	28	2.0	2.0	-	4	25	-	-
9	4.8	2.2	-	4	25	-	-	29	1.5	1.5	-	4	8	-	-
10	4.9	3.0	-	2	8	-	-	30	3.1	3.1	-	5	25	-	-
11	4.7	3.7	-	3	16	-	-	31	3.9	3.9	-	5	30	-	-
12	4.9	4.5	-	3	20	320	-	32	2.8	2.8	-	4	37	320	-
13	5.2	.5	-	5	25	-	-	33	2.2	2.2	-	4	16	-	4
14	4.7	.6	-	3	8	-	-	34	4.9	4.9	-	4	30	-	T
15	4.7	2.5	-	3	12	-	-	35	1.8	1.8	-	8	25	-	-
16	4.7	2.8	-	3	16	-	-	36	5.0	.3	-	4	20	-	T
17	5.1	2.6	-	5	25	-	-	37	5.0	6.9	-	4	34	-	6
18	4.6	9.3	-	11	37	-	-	38	4.8	3.8	-	3	8	-	-
19	4.5	2.6	-	11	49	-	-	39	5.0	2.2	-	3	8	320	-
20	5.0	2.2	-	3	8	320	-								

[a]Not present
[b]Trace only

TABLE 14.--Continued

WEXFORD COUNTY

Plot number	pH	Organic matter content	Major elements					Plot number	pH	Organic matter content	Major elements				
			N	P	K	C	Mg				N	P	K	C	Mg
	-Log.-	--%--	--Pounds per acre--						-Log.-	--%--	--Pounds per acre--				
40	5.7	1.5	10	2	34	-[a]	-	53	5.9	2.5	-	4	-	-	T[b]
41	5.5	.9	-	5	12	-	-	54	1.9	1.9	-	4	12	-	-
42	5.5	2.3	-	4	-	-	-	55	5.4	2.0	-	5	45	-	-
43	5.3	4.3	T	6	30	-	-	56	5.4	1.9	-	5	8	-	-
44	5.4	2.0	-	4	16	-	-	57	5.4	1.8	-	3	12	-	-
45	5.4	2.7	10	4	-	-	-	58	5.8	1.9	T	3	20	-	T
46	5.4	2.0	16	3	4	-	-	59	5.7	2.1	-	3	4	-	-
47	5.9	4.3	10	2	8	-	32	60	5.9	2.9	-	4	20	320	T
48	5.6	2.1	-	4	34	-	-	61	5.7	4.5	-	5	34	320	T
49	5.7	2.1	-	3	8	-	T	62	5.2	1.3	-	3	-	-	-
50	5.6	1.7	-	4	16	-	-	63	5.3	1.6	-	3	16	-	-
51	5.4	1.8	-	6	8	-	-	64	5.8	.9	-	3	20	-	-
52	4.8	1.8	10	5	41	320	-	65	5.8	.9	-	4	20	-	-

[a]Not present.

[b]Trace only.

TABLE 15.--The available water in inches per foot of horizon for 10 soil series in Michigan[a]

Soil series	Horizon									
	One-storied soils								Two-storied soils	
	Over-burden	A1 A2 Ap	Bh Bhir B2h B2hir	Bir B2ir	B22 B22ir	B3	C	D	A2	B2t
	Inches of water									
AuGres	1.26	1.70	1.45	1.45	1.50	1.50	.65	---	---	---
Saugatuck	1.26	1.70	1.50	1.50	1.50	1.50	.65	---	---	---
Croswell	1.26	1.70	1.55	1.55	1.45	1.45	.65	---	---	---
Rubicon	1.26	1.70	1.30	1.30	1.30	1.25	.60	---	---	---
Graycalm	1.26	1.60	1.35	1.35	1.35	.70	.65	---	---	2.00
Kalkaska	1.26	1.75	1.45	1.65	1.65	1.60	.65	---	---	---
East Lake	1.26	1.75	1.45	1.45	1.45	1.55	---	.65	---	---
Free Soil	1.26	1.65	1.45	1.45	1.35	1.55	.90	---	2.35	2.35
Antrim	1.75	1.75	1.50	1.45	1.55	1.60	.65	---	---	---
Blue Lake	1.26	1.70	1.45	1.45	1.65	2.35	.90	---	.90	2.35

[a]These are unpublished data from the Soil Science Department, Michigan State University. I am indebted to Dr. E.P. Whiteside for making them available in September, 1960.

TABLE 16.--The storage capacity of the root zone on the plots. Based on the capacity per horizon within the depth of maximum rooting

OTTAWA COUNTY

Plot number	Storage capacity	Plot number	Storage capacity	Plot number	Storage capacity
	Inches		Inches		Inches
1	3.0	14	.6	27	4.1
2	2.0	15	6.2	28	5.6
3	7.8	16	6.7	29	6.9
4	5.3	17	7.8	30	5.8
5	5.2	18	2.4	31	5.8
6	3.1	19	5.2	32	4.4
7	6.0	20	2.6	33	2.9
8	2.7	21	4.5	34	3.9
9	3.1	22	4.4	35	4.9
10	2.0	23	10.3	36	.6
11	4.4	24	5.3	37	3.9
12	2.9	25	4.4	38	4.7
13	.6	26	2.9	39	9.1

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40	7.8	49	5.2	58	4.7
41	7.2	50	6.4	59	6.2
42	11.3	51	5.8	60	7.5
43	6.0	52	7.5	61	6.8
44	7.0	53	6.5	62	1.6
45	3.8	54	5.7	63	4.3
46	5.7	55	5.1	64	.5
47	6.5	56	5.7	65	1.0
48	9.7	57	6.1		

TABLE 17.--U.S. Weather Bureau Station from which the mean monthly precipitation and temperature were determined[a]

County	U.S. Weather Bureau Station	
	Precipitation	Temperature
Ottawa	Holland, Hope College	Holland, Hope College
	Grand Haven, Fire Dept.	Grand Haven, Fire Dept.
	Grand Rapids, WB APR	Grand Rapids, WB APR
	Muskegon, WB AP	Muskegon, WB AP
	Kent City, 2 SW	
Wexford	Cadillac, CAA AP	Cadillac, CAA AP
	Lake City, Expt. Farm	Lake City, Expt. Farm
	Fife Lake, State Forest	Fife Lake, State Forest
	Wellston, Tippy Dam	
	Thompsonville	

[a]For exact location see: U.S. Weather Bureau Climatological Data, Michigan, Annual Summary. 1960.

TABLE 18.--The mean monthly precipitation on the study areas during 1939-1959[a]

OTTAWA COUNTY

Year	Month											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	--Inches of water--											
1939	2.3	2.8	1.1	3.2	1.1	5.1	1.2	4.4	2.7	2.4	.7	1.2
1940	2.4	.6	1.5	1.8	4.0	4.3	1.1	8.0	1.5	2.8	3.0	1.8
1941	1.9	1.1	2.1	1.9	3.1	1.3	1.8	3.4	6.7	5.9	3.7	1.6
1942	1.8	.9	3.0	.6	4.9	3.6	3.6	3.2	5.0	3.6	4.2	3.3
1943	2.1	1.9	2.5	2.0	5.0	2.8	2.1	2.4	1.9	1.4	2.4	.7
1944	1.3	1.9	2.7	2.7	1.9	4.3	2.9	2.2	3.8	.4	2.2	1.6
1945	.8	1.5	1.6	3.8	5.6	3.7	1.7	3.0	6.3	2.3	2.5	1.7
1946	2.3	1.7	2.5	1.1	3.2	3.0	1.3	1.8	1.8	2.3	3.2	2.6
1947	2.7	1.4	1.7	6.7	5.1	3.2	2.5	2.2	6.2	.8	2.8	2.2
1948	1.6	1.6	5.5	3.9	4.1	3.2	2.5	.9	1.9	1.0	3.1	2.4
1949	2.8	2.5	2.7	1.8	1.3	3.5	5.8	1.1	2.4	1.8	1.7	4.9
1950	4.0	2.5	2.4	5.3	1.3	3.9	5.2	1.9	1.8	1.3	2.4	3.4
1951	2.1	2.2	2.0	4.1	1.9	4.4	.8	3.5	4.4	3.8	3.9	3.1
1952	2.4	.9	2.7	2.5	3.7	2.1	6.7	3.7	2.4	.6	3.8	2.1
1953	1.5	2.1	1.8	2.8	2.9	4.3	2.1	2.8	2.6	1.7	1.4	1.9
1954	2.0	2.5	3.9	4.7	2.2	5.1	3.6	2.2	2.2	7.9	1.7	2.3
1955	1.8	1.7	2.2	2.4	3.1	2.7	2.1	3.3	1.4	3.4	3.3	1.2
1956	.4	1.7	2.4	3.8	6.1	1.8	3.4	2.6	.9	.5	1.7	1.4
1957	1.9	2.4	2.2	3.4	4.7	4.9	2.7	2.0	2.0	3.3	3.7	2.2
1958	1.6	1.1	.6	1.8	1.8	2.3	2.7	3.8	3.8	2.8	3.5	1.1
1959	2.1	2.7	3.1	4.0	2.8	.9	2.7	4.0	1.6	6.0	3.5	2.9

[a]Data for each county based on data compiled from five surrounding U.S. Weather Bureau Stations.

TABLE 18.--Continued[a]

WEXFORD COUNTY

Year	Month											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	--Inches of water--											
1939	2.1	1.6	1.0	1.7	2.7	4.8	1.1	6.5	3.2	2.2	.9	1.3
1940	2.0	.8	1.1	2.5	4.0	3.9	2.1	6.3	2.5	2.7	3.5	1.3
1941	1.9	1.1	.9	2.3	2.3	1.4	2.2	1.6	5.7	6.6	2.9	1.5
1942	1.9	.9	3.3	1.4	5.0	3.5	3.4	1.4	6.3	1.7	2.4	3.0
1943	1.7	1.8	3.1	2.2	2.8	5.8	2.8	2.8	1.3	3.0	3.8	1.3
1944	1.3	1.6	2.2	2.1	2.4	5.5	3.1	1.9	5.5	1.4	2.8	1.8
1945	1.6	1.8	1.6	3.4	5.8	4.3	4.3	4.0	5.0	3.3	5.0	1.5
1946	2.9	1.8	1.4	.8	2.9	2.9	1.9	1.2	3.3	1.4	3.3	2.8
1947	2.3	1.4	1.8	4.3	6.0	1.2	2.8	1.2	5.6	1.0	2.3	1.7
1948	1.3	1.4	3.0	3.2	2.0	3.3	3.0	1.8	1.5	.8	4.1	2.0
1949	2.4	2.0	2.2	2.1	1.9	5.3	4.0	1.6	2.4	1.7	2.9	2.7
1950	3.5	1.7	2.4	3.2	1.8	2.3	3.5	3.8	3.1	2.8	2.5	2.1
1951	2.2	1.9	2.6	4.6	1.8	1.8	4.4	3.1	3.3	5.0	3.3	2.5
1952	2.8	.9	2.6	2.2	1.7	2.3	6.9	3.7	1.3	.7	4.4	2.2
1953	1.9	3.2	1.7	2.9	3.1	3.8	3.7	3.0	3.0	1.2	1.4	1.9
1954	2.0	1.7	1.3	5.4	2.7	6.9	2.8	.8	4.2	6.5	1.4	1.5
1955	1.5	1.0	1.5	2.1	2.7	2.7	3.4	2.6	.8	3.3	2.1	1.9
1956	.4	1.1	2.4	3.1	3.3	2.4	3.8	5.5	1.6	1.0	2.5	1.5
1957	1.4	.6	.9	2.8	3.8	3.5	4.7	2.5	1.6	1.9	2.9	1.7
1958	.8	.8	.4	2.0	1.3	2.8	2.8	3.9	4.0	2.4	3.7	1.5
1959	1.7	2.1	1.7	4.4	3.3	1.2	2.3	4.7	3.2	5.5	2.7	1.6

[a]Data for each study area based on data compiled from five surrounding U.S. Weather Bureau Stations.

TABLE 19.--The mean monthly temperature for 1939-1959 inclusive[a]

OTTAWA COUNTY

Year	Month											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	--Degrees Fahrenheit--											
1939	28.9	26.6	33.8	42.5	58.8	68.6	71.7	70.8	65.6	52.7	39.9	34.5
1940	20.5	27.3	28.9	42.7	53.1	65.0	72.9	69.2	61.6	53.0	37.5	31.7
1941	26.6	24.2	29.9	51.7	59.2	68.6	71.9	69.1	65.5	53.0	42.3	35.5
1942	25.6	22.1	37.2	51.0	58.4	67.6	71.2	69.5	60.9	52.3	40.0	26.1
1943	21.1	26.4	29.7	41.8	55.1	68.9	72.1	70.7	59.8	50.1	36.8	28.0
1944	30.8	27.8	30.4	43.1	60.7	69.1	71.4	72.4	64.1	50.3	42.0	25.8
1945	19.9	26.9	45.7	48.8	51.5	62.5	68.8	69.0	62.0	49.8	41.2	25.0
1946	27.3	25.8	45.1	47.9	55.3	65.7	71.4	67.2	63.4	56.2	42.6	32.0
1947	28.5	22.6	30.8	44.1	51.3	64.1	69.4	77.3	65.5	60.3	36.8	30.1
1948	20.0	24.5	33.8	50.4	53.3	63.8	72.4	71.2	66.3	50.0	44.0	30.5
1949	29.2	28.1	34.9	45.3	58.6	70.6	75.5	70.9	58.6	55.9	38.8	32.3
1950	29.9	25.4	29.9	39.6	57.6	64.9	67.9	64.3	60.8	55.2	35.9	25.2
1951	25.7	27.1	34.5	44.5	59.1	64.4	68.9	66.2	60.2	53.2	32.2	28.3
1952	27.9	29.5	32.8	47.9	55.7	69.3	73.3	69.5	63.7	46.3	41.6	32.1
1953	28.7	30.4	36.8	43.3	58.2	69.2	73.4	71.3	62.9	54.9	44.5	33.6
1954	24.9	33.8	32.3	49.1	53.5	69.6	69.9	68.5	63.7	52.2	41.1	29.9
1955	25.6	26.3	33.9	52.7	59.4	66.1	76.9	75.1	62.2	53.9	35.3	25.5
1956	25.7	26.3	30.9	44.0	55.3	69.2	69.3	69.7	60.4	56.5	42.4	32.8
1957	21.7	29.2	35.1	47.2	55.9	67.2	72.2	68.9	60.4	49.3	40.0	32.6
1958	25.2	22.0	35.3	47.6	56.6	61.5	69.5	69.7	62.2	53.7	41.6	22.1
1959	19.6	23.6	32.1	45.3	62.2	68.7	71.3	75.1	65.9	49.7	34.4	33.5

[a]Data for this study area is based on four U.S. Weather Bureau Stations.

TABLE 19.--Continued[a]

WEXFORD COUNTY

Year	Month											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	--Degrees Fahrenheit--											
1939	21.3	17.5	25.7	38.2	56.6	64.6	68.9	67.4	59.1	45.8	35.6	28.6
1940	15.1	19.5	22.1	36.4	51.0	62.2	67.7	64.2	57.7	46.5	33.0	25.6
1941	20.0	18.4	21.7	46.9	55.5	64.2	68.2	63.8	60.1	46.1	36.6	29.3
1942	18.9	16.9	30.0	46.5	52.6	62.4	65.2	64.8	55.1	46.1	33.7	19.8
1943	14.5	18.5	20.5	37.2	50.2	65.4	66.0	64.7	54.1	44.7	31.0	21.1
1944	24.8	20.7	23.6	36.3	57.1	64.2	65.8	66.3	58.4	44.7	37.6	19.9
1945	13.7	20.8	40.2	44.6	47.8	58.4	63.9	65.0	56.4	44.5	35.2	19.1
1946	20.5	17.3	39.0	42.2	50.3	61.5	66.5	62.4	58.6	50.8	36.9	24.2
1947	22.4	15.6	23.2	38.5	47.7	60.9	66.4	72.6	59.8	55.7	30.4	22.9
1948	12.5	15.7	24.8	46.8	49.5	61.3	67.1	66.4	60.6	44.8	38.5	24.8
1949	23.1	21.4	26.9	41.5	54.4	67.0	69.5	66.8	54.6	50.9	32.4	25.3
1950	22.8	18.6	22.1	33.6	52.7	62.9	64.9	61.4	56.3	50.9	31.0	20.6
1951	17.9	20.8	27.2	41.1	57.0	60.4	65.7	62.6	55.2	48.2	25.8	22.5
1952	22.2	21.2	24.6	43.6	52.1	65.2	69.3	64.4	58.3	40.8	35.9	27.9
1953	22.2	22.2	30.3	39.2	53.7	64.2	67.0	65.8	56.8	50.1	39.4	27.6
1954	16.9	26.8	24.9	43.0	47.9	65.4	64.9	63.9	57.7	47.2	37.0	21.4
1955	18.4	19.2	26.4	48.4	56.1	62.9	72.2	70.8	57.3	50.4	31.5	21.4
1956	19.4	19.5	22.8	38.5	50.9	65.5	64.5	65.2	54.1	52.1	36.0	26.7
1957	14.4	22.1	29.3	43.6	52.6	63.6	67.7	63.9	55.8	45.0	34.9	25.4
1958	20.1	15.9	30.9	43.8	52.0	57.7	65.7	65.2	57.2	49.8	36.3	14.5
1959	12.8	14.8	25.4	41.5	59.1	64.8	68.5	71.2	60.6	44.8	28.5	27.9

[a]Data for this study area is based on three U.S. Weather Bureau Stations.

TABLE 20.--The monthly potential evapo-transpiration of the study areas during 1939-1959

OTTAWA COUNTY

Year	Month											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	--Inches of water--											
1939	--[a]	--	.1	.9	3.4	4.3	5.6	4.9	3.6	1.8	.6	.2
1940	--	--	--	1.5	2.8	4.5	5.7	4.9	3.3	1.8	.4	--
1941	--	--	--	1.9	3.3	4.9	5.7	4.7	3.5	1.8	.7	.1
1942	--	--	.3	1.9	3.3	4.8	5.5	4.8	3.1	1.8	.5	--
1943	--	--	--	.9	2.9	5.2	5.7	4.9	3.0	1.6	.3	--
1944	--	--	--	.9	3.6	5.0	5.5	5.2	3.3	1.6	.6	--
1945	--	--	1.4	1.8	2.4	4.1	5.2	4.9	3.2	1.6	.5	--
1946	--	--	1.1	1.6	2.9	4.3	5.5	4.4	3.3	2.2	.7	--
1947	--	--	--	1.1	2.2	4.2	5.2	5.8	3.6	2.7	.3	--
1948	--	--	.1	2.6	2.5	4.2	5.8	5.6	3.7	1.6	.8	--
1949	--	--	.2	1.4	3.2	5.2	5.9	4.9	2.7	2.2	.3	--
1950	--	--	--	.8	3.4	4.4	5.0	4.1	3.2	2.2	.3	--
1951	--	--	.2	1.3	3.5	4.4	5.3	4.5	2.7	2.0	--	--
1952	--	--	.1	1.7	2.9	5.1	5.9	4.9	3.3	1.2	.6	--
1953	--	--	.3	1.3	3.2	5.1	5.6	5.1	3.3	2.1	.9	--
1954	--	--	--	1.7	2.7	5.1	5.2	4.7	3.3	1.9	.6	--
1955	--	--	.1	2.1	3.3	3.6	6.3	5.4	3.1	1.9	2.1	--
1956	--	--	--	1.2	3.0	5.1	5.3	4.9	3.0	2.3	.7	--
1957	--	--	--	2.0	3.5	5.4	6.5	5.9	4.3	2.4	.9	--
1958	--	--	2.2	1.7	3.1	3.9	5.3	4.9	3.3	2.0	.7	--
1959	--	--	--	1.2	4.0	4.9	5.5	5.6	3.5	1.4	--	--

[a]There was no monthly potential evapo-transpiration during these months.

TABLE 20.--Continued

WEXFORD COUNTY

Year	Month											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	--Inches of water--											
1939	--[a]	--	--	.7	3.2	4.7	5.3	4.7	2.9	1.3	.3	--
1940	--	--	--	.5	2.7	4.3	5.3	4.5	3.0	1.5	--	--
1941	--	--	--	1.8	3.1	4.5	5.2	4.1	3.1	1.3	.3	--
1942	--	--	--	1.7	2.9	4.4	5.0	4.4	2.7	1.4	.1	--
1943	--	--	--	.6	2.6	4.8	5.0	4.4	2.6	1.3	--	--
1944	--	--	--	.5	3.3	3.2	4.9	4.6	3.0	1.2	.4	--
1945	--	--	.9	2.1	2.2	3.9	4.7	4.5	2.9	1.3	.3	--
1946	--	--	.7	1.3	2.5	4.2	5.0	4.0	3.0	1.6	.4	--
1947	--	--	--	.7	2.1	4.1	4.9	5.4	3.1	2.4	--	--
1948	--	--	--	1.6	2.2	4.1	4.9	4.4	3.1	1.1	.5	--
1949	--	--	--	1.0	3.0	5.0	5.4	4.6	2.5	1.8	--	--
1950	--	--	--	.2	2.9	4.4	4.6	3.9	2.9	2.0	--	--
1951	--	--	--	1.2	3.5	4.2	4.9	4.1	2.7	1.7	--	--
1952	--	--	--	1.4	2.8	4.7	5.4	4.3	3.0	.8	.3	--
1953	--	--	--	.8	2.9	4.5	5.4	4.5	2.8	1.8	.5	--
1954	--	--	--	1.3	2.2	4.8	4.8	4.4	3.0	1.6	.3	--
1955	--	--	--	1.8	3.1	4.1	5.8	5.2	2.7	1.6	--	--
1956	--	--	--	.7	2.7	4.8	4.4	3.9	2.5	2.1	.4	--
1957	--	--	--	1.8	3.4	5.0	5.9	5.3	3.8	2.1	.3	--
1958	--	--	--	1.4	2.8	3.7	4.9	4.4	3.0	1.8	.3	--
1959	--	--	--	.1	3.6	4.5	5.0	5.3	3.1	1.2	--	--

[a]There was no monthly potential evapo-transpiration during these months.

TABLE 21.--The relationship between the water required and the water supplied by soils with a maximum storage capacity of 2 and 4 inches. The water required is the accumulated difference between precipitation and the potential evapo-transpiration[a]

Water required	Total Maximum storage		Water required	Total Maximum storage	
	2	4		2	4
	--Inches--			--Inches--	
-	-	-	6.0	2.00	3.15
0.2	0.20	0.20	6.2	2.00	3.20
.4	.39	.39	6.4	2.00	3.25
.6	.55	.55	6.6	2.00	3.30
.8	.75	.75	6.8	2.00	3.35
1.0	.85	.92	7.0	2.00	3.38
1.2	1.00	1.10	7.2	2.00	3.40
1.4	1.10	1.20	7.4	2.00	3.43
1.6	1.20	1.35	7.6	2.00	3.45
1.8	1.30	1.45	7.8	2.00	3.47
2.0	1.35	1.60	8.0	2.00	3.50
2.2	1.45	1.70	8.2	2.00	3.52
2.4	1.50	1.80	8.4	2.00	3.54
2.6	1.55	1.90	8.6	2.00	3.56
2.8	1.60	2.00	8.8	2.00	3.58
3.0	1.65	2.10	9.0	2.00	3.61
3.2	1.70	2.20	9.2	2.00	3.63
3.4	1.75	2.30	9.4	2.00	3.65
3.6	1.80	2.35	9.6	2.00	3.67
3.8	1.85	2.45	9.8	2.00	3.69
4.0	1.90	2.55	10.0	2.00	3.72
4.2	1.93	2.60	10.2	2.00	3.74
4.4	1.95	2.65	10.4	2.00	3.76
4.6	2.00	2.75	10.6	2.00	3.77
4.8	2.00	2.80	10.8	2.00	3.78
5.0	2.00	2.85	11.0	2.00	3.79
5.2	2.00	2.90	11.2	2.00	3.80
5.4	2.00	2.95	11.4	2.00	3.81
5.6	2.00	3.00	11.6	2.00	3.82
5.8	2.00	3.05	11.8	2.00	3.83

[a]This is an extrapolation of Zahner's Table 1 (1956).

TABLE 22.--The monthly water requirement on the study areas during 1939-1959

OTTAWA COUNTY

Year	Month											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	--Inches of water--											
1939	--[a]	--	--	--	2.3	--	4.4	.5	.9	--	--	--
1940	--	--	--	--	--	.2	4.6	--	1.8	--	--	--
1941	--	--	--	--	.2	3.6	3.9	1.3	--	--	--	--
1942	--	--	--	1.3	--	1.2	1.8	1.7	--	--	--	--
1943	--	--	--	--	--	2.4	3.5	2.6	1.1	.2	--	--
1944	--	--	--	--	1.7	.7	2.6	3.0	--	1.1	--	--
1945	--	--	--	--	--	.4	3.6	1.8	--	--	--	--
1946	--	--	--	.5	--	1.4	4.2	2.6	1.5	.1	--	--
1947	--	--	--	--	--	1.1	2.8	3.6	--	1.9	--	--
1948	--	--	--	--	--	1.0	3.2	4.2	1.9	.6	--	--
1949	--	--	--	--	1.9	1.7	.1	3.8	.3	.4	--	--
1950	--	--	--	--	2.5	.5	.2	2.2	1.4	1.1	--	--
1951	--	--	--	--	1.7	--	4.5	1.0	--	--	--	--
1952	--	--	--	--	--	3.1	--	1.2	.9	.7	--	--
1953	--	--	--	--	.3	.9	3.6	2.3	.7	.4	--	--
1954	--	--	--	--	.5	--	1.6	2.5	1.1	--	--	--
1955	--	--	--	--	.2	1.0	4.2	2.1	1.7	--	--	--
1956	--	--	--	--	--	3.3	1.9	2.3	2.1	1.8	--	--
1957	--	--	--	--	--	.5	3.8	3.9	2.3	--	--	--
1958	--	--	1.7	--	1.4	1.6	2.6	1.2	--	--	--	--
1959	--	--	--	--	1.2	4.0	2.8	1.6	1.9	--	--	--

[a]Water needs did not occur during these months.

TABLE 22.--Continued

WEXFORD COUNTY

Year	Month											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	--Inches of water--											
1939	--[a]	--	--	--	.5	--	4.2	--	--	--	--	--
1940	--	--	--	--	--	.4	3.2	--	.5	--	--	--
1941	--	--	--	--	.8	3.1	3.1	2.6	--	--	--	--
1942	--	--	--	.4	--	.9	1.6	3.0	--	--	--	--
1943	--	--	--	--	--	--	2.2	1.6	1.3	--	--	--
1944	--	--	--	--	.9	--	1.8	2.8	--	--	--	--
1945	--	--	--	--	--	--	.4	.4	--	--	--	--
1946	--	--	--	.5	--	1.4	3.1	2.8	--	.2	--	--
1947	--	--	--	--	--	2.9	2.1	4.2	--	1.4	--	--
1948	--	--	--	--	.2	.8	1.9	2.6	1.6	--	--	--
1949	--	--	--	--	1.1	--	1.3	3.0	.1	.1	--	--
1950	--	--	--	--	1.2	2.2	1.1	.2	--	--	--	--
1951	--	--	--	--	1.7	2.4	.5	1.0	--	--	--	--
1952	--	--	--	--	1.1	2.4	--	.7	1.7	.2	--	--
1953	--	--	--	--	--	.7	1.7	1.5	--	.6	--	--
1954	--	--	--	--	--	--	2.0	3.6	--	--	--	--
1955	--	--	--	--	.4	1.4	2.4	2.5	1.9	--	--	--
1956	--	--	--	--	--	2.4	.6	1.6	.9	1.0	--	--
1957	--	--	--	--	--	1.5	1.3	2.8	2.2	.1	--	--
1958	--	--	--	--	1.5	.9	2.2	.6	--	.6	--	--
1959	--	--	--	--	.3	3.3	2.7	.6	.1	--	--	--

[a]Water needs did not occur during these months.

TABLE 23.--The accumulative monthly water requirement on the study areas during 1939-1959

OTTAWA COUNTY

Year	Month											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	--Inches of water--											
1939	-- [a]	--	--	--	2.3	1.5	4.4	4.9	5.7	--	--	--
1940	--	--	--	--	--	.2	4.8	1.6	1.8	--	--	--
1941	--	--	--	--	.2	3.8	7.7	9.0	--	--	--	--
1942	--	--	--	1.3	--	1.2	3.0	4.7	--	--	--	--
1943	--	--	--	--	--	2.4	5.9	8.5	9.6	9.7	--	--
1944	--	--	--	--	1.7	2.4	5.0	8.1	7.5	8.6	--	--
1945	--	--	--	--	--	.4	4.0	5.8	--	--	--	--
1946	--	--	--	.5	.2	1.4	5.6	8.2	9.7	9.8	--	--
1947	--	--	--	--	--	1.1	3.8	7.5	4.9	1.9	--	--
1948	--	--	--	--	--	1.0	4.3	8.5	10.4	10.9	--	--
1949	--	--	--	--	1.9	3.7	3.8	7.6	7.8	8.2	--	--
1950	--	--	--	--	2.1	2.6	2.8	5.0	6.4	7.5	--	--
1951	--	--	--	--	1.7	1.7	6.2	7.2	--	--	--	--
1952	--	--	--	--	--	3.1	2.3	1.2	2.1	2.8	--	--
1953	--	--	--	--	.3	1.2	4.8	7.1	7.8	8.1	--	--
1954	--	--	--	--	.5	.5	2.2	4.6	5.8	--	--	--
1955	--	--	--	--	.2	1.2	5.3	7.4	9.1	--	--	--
1956	--	--	--	--	--	3.3	5.3	7.5	9.6	11.3	--	--
1957	--	--	--	--	--	.5	4.2	8.2	10.4	--	--	--
1958	--	--	1.7	1.6	1.4	3.0	5.6	6.8	--	--	--	--
1959	--	--	--	--	1.2	5.3	8.1	9.7	11.6	--	--	--

[a]Water needs did not occur during these months.

TABLE 23.--Continued

WEXFORD COUNTY

Year	Month											
	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
	--Inches of water--											
1939	--[a]	--	--	--	.5	.4	4.2	--	--	--	--	--
1940	--	--	--	--	--	.4	3.6	1.9	.5	--	--	--
1941	--	--	--	--	.8	3.8	6.9	9.4	--	--	--	--
1942	--	--	--	.4	--	.9	2.5	5.5	--	--	--	--
1943	--	--	--	--	--	--	2.2	3.9	5.1	--	--	--
1944	--	--	--	--	.9	--	1.8	4.6	--	--	--	--
1945	--	--	--	--	--	--	.4	.8	--	--	--	--
1946	--	--	--	.5	.1	1.4	4.5	7.3	7.0	7.2	--	--
1947	--	--	--	--	--	2.9	5.0	9.2	6.3	1.4	--	--
1948	--	--	--	--	.2	1.0	2.8	5.4	7.0	--	--	--
1949	--	--	--	--	1.1	.8	1.3	4.3	4.4	4.5	--	--
1950	--	--	--	--	1.2	3.3	4.4	4.6	--	--	--	--
1951	--	--	--	--	1.7	4.1	4.6	5.5	--	--	--	--
1952	--	--	--	--	1.1	3.6	2.0	.7	2.4	2.6	--	--
1953	--	--	--	--	--	.7	2.5	3.9	3.7	.6	--	--
1954	--	--	--	--	--	--	2.0	5.6	--	--	--	--
1955	--	--	--	--	.4	1.8	4.2	6.8	8.6	--	--	--
1956	--	--	--	--	--	2.4	3.0	4.6	5.5	6.6	--	--
1957	--	--	--	--	--	1.5	2.8	5.6	7.8	8.0	--	--
1958	--	--	--	--	--	1.5	2.3	4.5	5.1	4.0	.6	--
1959	--	--	--	--	.3	3.5	6.2	6.7	6.8	--	--	--

[a]Water needs did not occur during these months.

TABLE 24.--Significant variables affecting the mean annual number of branches per whorl in shoot moth infested red pine in Ottawa County, Michigan. The branches per whorl can be derived by algebraically adding the partial predicted values associated with the independent variables

Significant independent variables		Partial predicted values			
X 9: Age of tree since planting in years		5	10	15	20
		--Partial predicted values--			
X11: Internodal distance in inches	6	15.9	15.0	14.2	[a]
	12	17.1	16.3	15.4	[a]
	18	18.3	17.5	16.7	15.8
	24	[a]	18.7	17.9	17.1
	30	[a]	20.0	19.2	18.3
X26: Mean July temperature previous year, degrees fahrenheit		65	68	71	74
		--Partial predicted values--			
X24: Mean April temperature current year	40	-7.5	-7.7	-7.9	-8.7
	43	-7.7	-7.9	-8.1	-8.4
	46	-7.9	-8.1	-8.4	-8.6
	49	-8.1	-8.3	-8.6	-8.8
X22: Mean June temperature current year, degrees fahrenheit		60	63	66	69
		--Partial predicted values--			
		-5.2	-5.4	-5.7	-6.0
X 3: July percent of storage capacity current year, percent		20	40	60	80
		--Partial predicted values--			
		.3	.6	.9	1.2

[a]Data did not include these conditions.

TABLE 25.--The mean annual number of branches per whorl in shoot moth infested red pine in Ottawa County, Michigan, as influenced by significant variables

Significant independent variables		Mean annual number of branches per whorl							
X 7: July percentage of storage capacity, previous year		20 %				40 %			
X 9: Age since planting, in years		5	10	15	20	5	10	15	20
		--Branches per whorl--							
X11: Mean annual periodic height increment, in inches	6	1.7	1.2	.7	--[a]	2.3	1.8	1.3	--
	12	3.0	2.5	2.0	--	3.5	3.0	2.6	--
	18	4.3	3.8	3.3	2.8	4.8	4.3	3.8	3.3
	24	--	5.0	4.5	4.0	--	5.6	5.1	4.6
	30	--	6.3	5.8	5.3	--	6.8	6.4	5.9
X 7: July percentage of storage capacity, previous year		60 %				80 %			
X 9: Age since planting, in years		5	10	15	20	5	10	15	20
		--Branches per whorl--							
X11: Mean annual periodic height increment, in inches	6	2.8	2.3	1.8	--	3.4	2.9	2.4	--
	12	4.1	3.6	3.1	--	4.6	4.1	3.6	--
	18	5.4	4.9	4.4	3.9	5.9	5.4	4.9	4.4
	24	--	6.1	5.6	5.1	--	6.7	6.2	5.7
	30	--	7.4	6.9	6.4	--	8.0	7.5	6.0

[a]Data do not cover this condition.

TABLE 26.--Significant variables affecting the percentage of bushing in shoot moth infested red pine in Ottawa County, Michigan. The percentage of bushing can be determined by algebraically adding the partial predicted values for the specific combinations of independent variables

Significant independent variables		Partial predicted values			
X 6: June percentage of storage capacity, previous year		20	40	60	80
		--Partial predicted values--			
X 7: July percentage of storage capacity, previous year	20	-41	-67	-93	-119
(includes X8, X16)	40	-52	-75	-98	-121
	60	-63	-83	-106	-122
	80	-74	-91	-108	-124
X 5: April percentage of storage capacity, current year		20	40	60	80
		--Partial predicted values--			
(includes X15)		-37	-61	-74	-74
X22: Mean June temperature, current year, degrees Fahrenheit		20	63	66	69
		--Partial predicted values--			
		49	52	54	57
X 2: June percentage of storage capacity, current year		20	40	60	80
		--Partial predicted values--			
X 3: July percentage of storage capacity, current year	20	92	89	87	85
(includes X4)	40	82	82	82	83
	60	71	75	78	81
	80	61	67	73	79

TABLE 27.--The influence of the significant variables affecting the percentage of the storage capacity during June in Ottawa County

Significant independent variables		Percentage of storage capacity during June								
		--Percent--								
X 2: Mean April temperature, degrees Fahrenheit		45								
X 8: Mean May precipitation, in inches		2			4			6		
X 9: Mean June precipitation, in inches		2	4	6	2	4	6	2	4	6
X11: Storage capacity of the root zone, in inches	2	21.05	48.31	75.57	36.82	64.08	91.35	52.59	79.86	100.00
	4	37.64	64.90	92.16	53.41	80.67	100.00	69.18	96.45	100.00
	6	54.23	81.49	100.00	70.00	97.26	100.00	85.77	100.00	100.00
	8	70.82	98.08	100.00	86.59	100.00	100.00	100.00	100.00	100.00
	10	87.41	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
	12	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
X 2: Mean April temperature, degrees Fahrenheit		50								
X 8: Mean May precipitation, in inches		2			4			6		
X 9: Mean June precipitation, in inches		2	4	6	2	4	6	2	4	6
X11: Storage capacity of the root zone, in inches	2	30.54	57.80	85.06	46.31	73.57	100.00	61.98	91.71	100.00
	4	47.13	74.39	100.00	62.90	90.16	100.00	78.57	100.00	100.00
	6	63.72	90.98	100.00	79.49	100.00	100.00	95.16	100.00	100.00
	8	80.13	100.00	100.00	96.08	100.00	100.00	100.00	100.00	100.00
	10	96.90	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
	12	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

TABLE 28.--The influence of the significant variables affecting the percentage of the storage capacity during July in Ottawa County

Significant independent variables		Percentage of storage capacity during July								
		--Percent--								
X 3: Mean May temperature, degrees Fahrenheit		55								
X 9: Mean June precipitation, in inches		2			4			6		
X10: Mean July precipitation, in inches		2	4	6	2	4	6	2	4	6
X11: Storage capacity of the root zone, in inches	2	19.87	33.40	46.94	26.81	40.35	53.88	33.76	47.29	60.83
	4	34.07	47.60	61.14	41.01	54.55	68.08	47.96	61.49	75.03
	6	48.27	61.80	75.34	55.21	68.75	82.28	62.16	75.69	89.23
	8	62.47	76.00	89.54	69.41	82.95	96.48	76.36	89.89	100.00
	10	76.67	90.20	100.00	83.61	97.15	100.00	90.56	100.00	100.00
	12	90.87	100.00	100.00	97.81	100.00	100.00	100.00	100.00	100.00
X 3: Mean May temperature, degrees Fahrenheit		60								
X 9: Mean June precipitation, in inches		2			4			6		
X10: Mean July precipitation, in inches		2	4	6	2	4	6	2	4	6
X11: Storage capacity of the root zone, in inches	2	8.84	22.37	35.91	15.78	29.32	42.85	22.73	36.26	49.80
	4	23.04	36.57	50.11	29.98	43.52	57.05	36.93	50.46	64.00
	6	37.24	50.77	64.31	44.18	57.72	71.25	51.13	14.66	78.20
	8	51.44	64.97	78.51	58.38	71.92	85.45	65.33	78.86	92.40
	10	65.64	79.17	92.71	72.58	86.12	99.65	79.53	93.06	100.00
	12	79.84	93.37	100.00	86.78	100.00	100.00	93.73	100.00	100.00

TABLE 29.--The influence of the significant variables affecting the percentage of storage capacity during July in Wexford County

Significant independent variables		percentage of storage capacity during July								
		--Percent--								
X 6: March precipitation, in inches		1								
X 9: June precipitation, in inches		2			4			6		
X10: July precipitation, in inches		2	4	6	2	4	6	2	4	6
X11: Storage capacity of the root zone, in inches	2	15.13	28.16	41.19	27.07	40.10	53.12	39.00	52.03	65.05
	4	29.70	42.74	55.77	41.65	54.68	67.70	53.58	66.61	79.63
	6	44.29	57.32	70.35	56.23	69.26	82.28	68.16	81.19	94.21
	8	58.87	71.90	84.93	70.81	83.84	96.86	82.74	95.77	100.00
	10	73.45	86.48	99.51	85.39	98.42	100.00	97.32	100.00	100.00
	12	88.03	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
X 6: March precipitation, in inches		2								
X 9: June precipitation, in inches		2			4			6		
X10: July precipitation, in inches		2	4	6	2	4	6	2	4	6
X11: Storage capacity of the root zone, in inches	2	24.31	37.34	50.37	36.25	49.28	62.31	48.19	61.22	74.24
	4	38.89	51.92	64.95	50.83	63.86	76.89	62.77	75.80	88.82
	6	53.47	66.50	79.53	65.41	78.44	91.47	77.35	90.38	100.00
	8	68.05	81.08	94.11	79.99	93.02	100.00	91.93	100.00	100.00
	10	82.63	95.66	100.00	94.57	100.00	100.00	100.00	100.00	100.00
	12	97.21	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
X 6: March precipitation, in inches		3								
X 9: June precipitation, in inches		2			4			6		
X10: July precipitation, in inches		2	4	6	2	4	6	2	4	6
X11: Storage capacity of the root zone, in inches	2	33.49	46.52	59.54	45.40	58.43	71.46	57.33	70.35	83.38
	4	48.07	61.10	74.13	59.98	73.01	86.04	71.91	84.93	97.96
	6	62.65	75.68	88.71	74.56	87.59	100.00	86.49	99.51	100.00
	8	77.23	90.26	100.00	89.14	100.00	100.00	100.00	100.00	100.00
	10	91.81	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
	12	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

TABLE 30.--The association of the storage capacity within the root zone and the maximum depth of red pine roots in the AuGres, Saugatuck, Rubicon and Kalkaska soil series in Ottawa and Wexford Counties, Michigan

Maximum rooting depth	Storage capacity of root zone	Maximum rooting depth	Storage capacity of root zone
--Inches--		--Inches--	
12	.8	66	5.5
18	1.9	72	5.7
24	2.7	78	6.0
30	3.3	84	6.2
36	3.8	90	6.4
42	4.3	96	6.5
48	4.6	102	6.7
54	5.0	108	6.9
60	5.2	114	7.0

TABLE 31.--The association of the depth to free water or mottling in the Rubicon, Kalkaska, Graycalm, East Lake and Free Soil soil series in Ottawa and Wexford Counties, Michigan

Depth to free water or mottling	Maximum rooting depth	Depth to free water or mottling	Maximum rooting depth
--Inches--		--Inches--	
24	20.1	78	65.0
30	25.1	84	70.0
36	30.0	90	75.0
42	35.0	96	80.0
48	40.0	102	85.0
54	45.0	108	90.0
60	50.0	114	95.0
66	55.0	120	100.0
72	60.0		

TABLE 32.--The association of the depth to texture-gravel bands and the maximum depth of red pine roots in the Rubicon, Graycalm, Kalkaska, Free Soil, and East Lake soil series in Ottawa and Wexford Counties, Michigan

Depth to texture-gravel bands	Maximum root depth	Depth to texture-gravel bands	Maximum root depth
Inches		Inches	
48	58.8	84	75.5
54	61.6	84	75.5
60	64.4	90	78.3
66	67.2	96	81.1
72	70.0	102	83.8
78	72.7	108	86.6

TABLE 33.--The relation between the number of shoot moth larvae and the number of red pine buds destroyed during the summer and spring feeding period

Summer feeding		Spring feeding	
Larvae	Buds destroyed	Larvae	Buds destroyed
--Number--		--Number--	
10	14.0	10	42.5
20	56.0	20	67.8
30	80.6	30	82.7
40	98.1	40	93.3
50	111.6	50	101.4

TABLE 34.--The relation of the number of red pine shoots with the height of the tree

Height of tree	Shoots per tree	Height of tree	Shoots per tree
--Inches--	--Number--	--Inches--	--Number--
12	8	60	68
24	13	72	104
36	23	84	201
48	40	96	346

TABLE 35.--The type and amount of stem damage to red pine following an outbreak of the shoot moth during the 1930's in Connecticut

Type of damage		Plantation I[a]		Plantation II[b]	
		--Percent--			
Undamaged trees		40		24	
Damaged trees		60		76	
Multiple damage			6		20
Single damage			54		56
Fork			27	13	30
Crook	2"		15	5	5
	4"		10	2	4
Posthorn			2	0	17

[a]Based on 100 percent cruise of a .1 acre plot, 52 trees. Site index II (Spurr, 1955).

[b]Based on a sample of every fifth tree, every fifth row for a total of 46 trees (approximately .8 acre plot). Site index VII (Spurr, 1955).

TABLE 36.--The type and amount of shoot moth damage to four-foot red pine pulp sticks following a 25-year-old infestation in two Connecticut red pine plantations

PLANTATION I

Height above ground (feet)	Years	Type of damage					
		Fork	Crook 2"	Crook 4"	Posthorn	Total	Percent
		--Number of 4-foot sticks--					
1 - 5	1919-1924	-	-	-	-	-	-
5 - 9	1924-1927	-	1	-	-	1	2.9
9 - 13	1927-1929	-	1	-	-	1	2.9
13 - 17	1929-1931	3	1	1	1	6	17.1
17 - 21	1931-1933	6	6	1	-	13	37.1
21 - 25	1933-1935	7	2	2	-	11	31.4
25 - 29	1935-1938	1	-	1	-	2	5.7
29 - 33	1938-1941	-	-	1	-	1	2.9
[a]33 - 52	1941-1958	-	-	-	-	-	-
Total		17	11	6	1	35	100.0

PLANTATION II

1 - 5	1934	1	6	4	-	11	24.4
5 - 9	1934-1937	-	1	-	-	1	2.2
9 - 13	1937-1940	1	1	1	1	4	8.9
13 - 17	1940-1942	4	-	1	1	6	13.3
17 - [b]21	1942-1945	12	-	-	3	15	33.3
[b]21 - 25	1945-1950	1	-	-	2	3	6.7
25 - 29	1950-1954	1	-	-	1	2	4.4
29 - 33	1954-1958	-	1	-	2	3	6.7

[a]All damage is below height of minimum 3-inch top as of 1958.

[b]Data above this height is above the minimum 3-inch top as of 1958.



Fig. 1.--The recognition of red pine buds damaged by the shoot moth provides a way to date an infestation. Left: 3-year-old red pine lateral buds destroyed by the shoot moth (Wexford Co., Mich.). Right; the destruction of these 4-year-old buds resulted in a complete reduction in the annual branches per whorl (Ottawa Co., Mich.).



Fig. 2.--Not all plantations succumb to the shoot moth. These 8-year-old red pine were attacked by the shoot moth when 2 years old, yet normal height growth has continued (Wexford Co., Mich.).



Fig. 3--The number of branches per fork or the loss of stem form depends on the number of buds destroyed and the degree of offset. Left: 2-year-old fork with the bud cluster destroyed by the shoot moth (Wexford Co., Mich.). Right: 34-year-old crook from Rose Pond, near New Haven, Conn.



Fig. 4.--Spring feeding on the outside of an elongating shoot by shoot moth larvae caused the weakened shoot to fall. If the shoot survives, a posthorn may develop. Left: Wexford Co., Mich. Right: near New Britain, Conn.



Fig. 5.--The bushing of terminals is a result of the growth of adventitious buds when the terminal bud cluster is destroyed. A lower lateral branch usually assumes dominance. Left: a 4-year-old bush (Wexford Co., Mich.). Right: a 27-year-old bush (Rose Pond, near New Haven, Conn.).

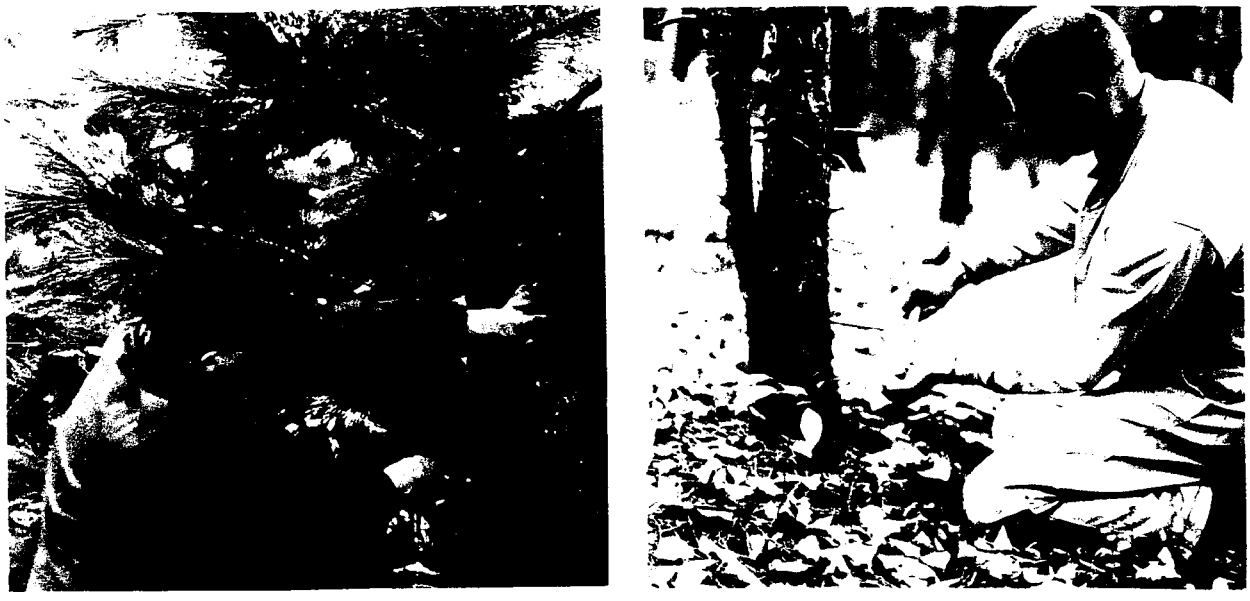


Fig. 6.--Dating the year a red pine tree is attacked by the shoot moth is facilitated by the characteristic of uninodal growth. Left: determining the year of attack by counting whorls (Carroll Co., Ohio). Right: using an increment borer to date the year of shoot moth attack (Eli Whitney Forest, Yale Univ., Conn.).



Fig. 7.--The first discovery of sharply delineated areas of varying shoot moth damage was by Dr. W.E. Miller in the spring of 1958. Dating old damage revealed both areas had been subject to attack for an equal length of time (Ottawa Co., Mich.).



Fig. 8.--During the field season of 1958, additional "islands" of near-normal trees were found in severely damaged plantations. These trees are in the midst of an entire section infested with the shoot moth in Oceana Co., Michigan. (T16N, R15W, Sec. 13)

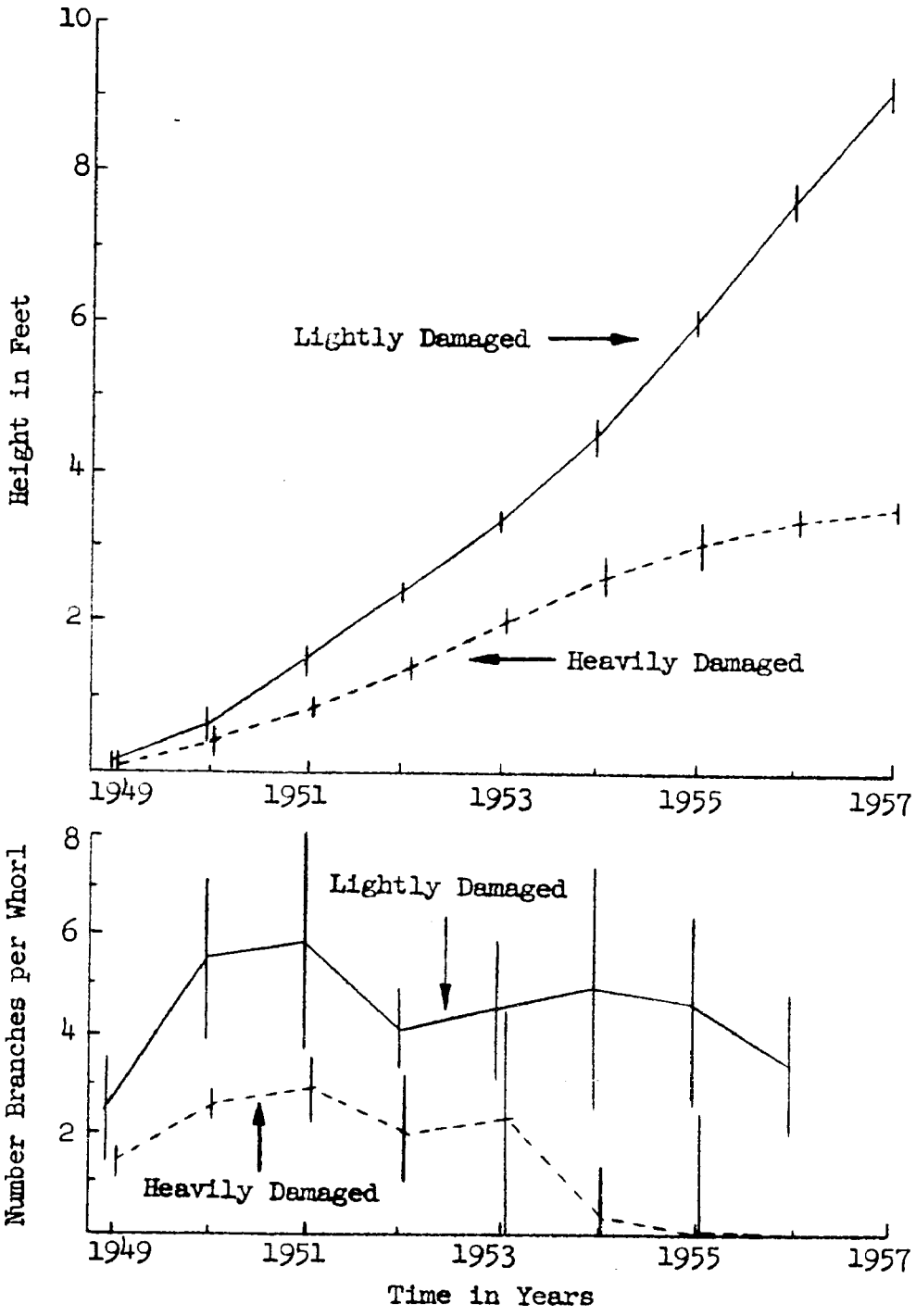


Fig. 9.--Shoot moth damage in adjacent areas can vary widely. This plantation (Fig. 7) was infested when planted. Plotting the mean annual height growth and the number of branches per whorl shows the significant differences in tree damage. Vertical bars show one standard deviation (Ottawa Co., Mich.).



Fig. 10.--In some red pine plantations, severely damaged trees are associated with geologic features. Trees on knobs are often damaged while trees in depressions may maintain normal growth (Wexford Co., Mich.).



Fig. 11.--During August, 1958, American forest entomologists visited the Canadian shoot moth studies at Elmira, Ontario. Damage appeared to be associated with topography. All trees have been equally exposed to attack by the shoot moth.

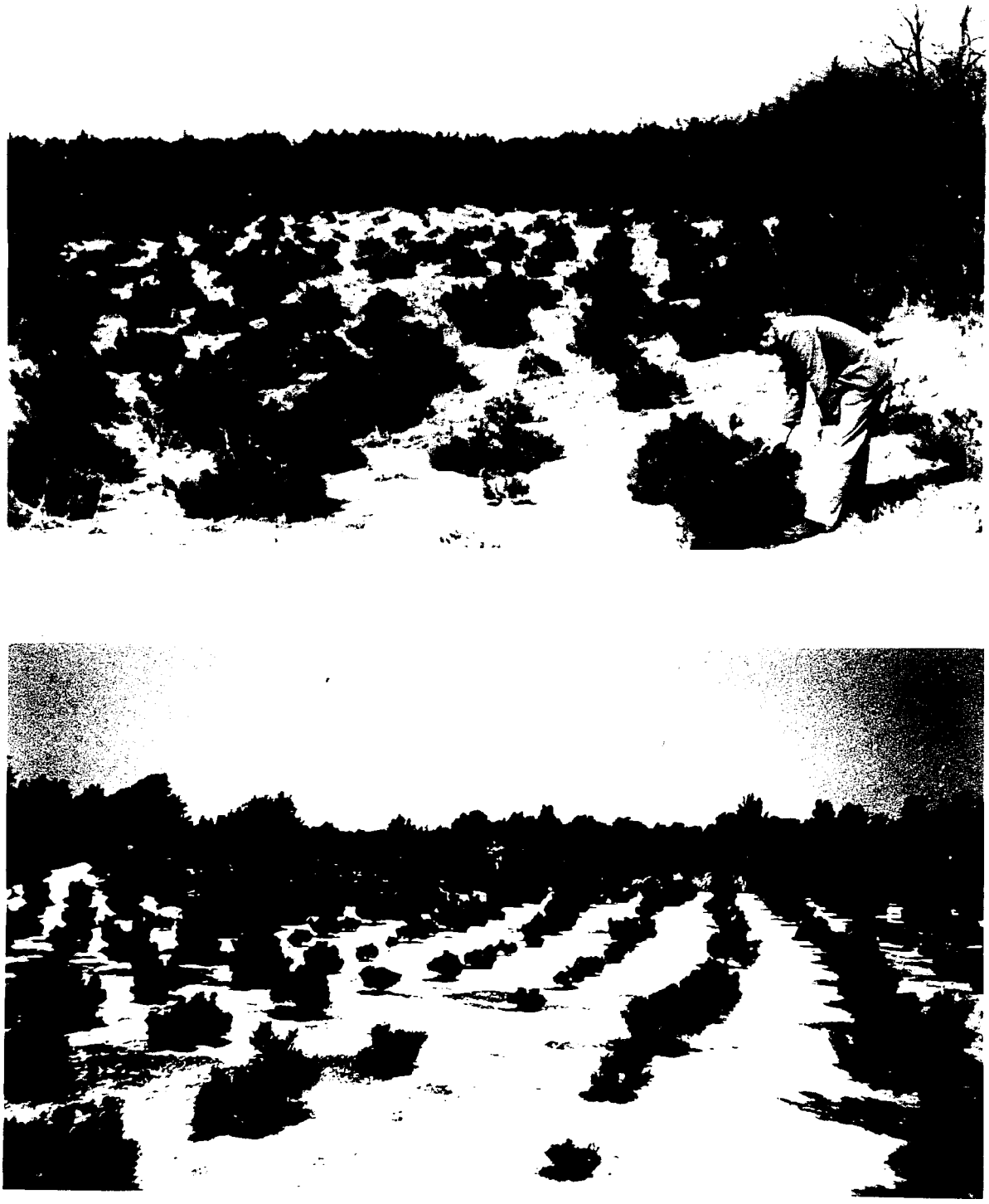


Fig. 12.--Some areas of red pine appear to be severely damaged year after year by the shoot moth. Above: these red pine growing on windblown sand are 13 years old and have been continuously damaged by the shoot moth. Below: these 10-year-old red pine have been attacked since planting (Ottawa Co., Mich.).



Fig. 13.--Some red pine plantations in infested areas appeared to have escaped the shoot moth, but close examination revealed the presence of past attacks. Above left: this 13-year-old plantation had been infested for 9 years (Wexford Co., Mich.). Above right: this plantation had been infested within 2 years after planting (Ottawa Co., Mich.). Below: on the Eli Whitney Forest (near New Haven, Conn.) many plantations have not succumbed to attack.

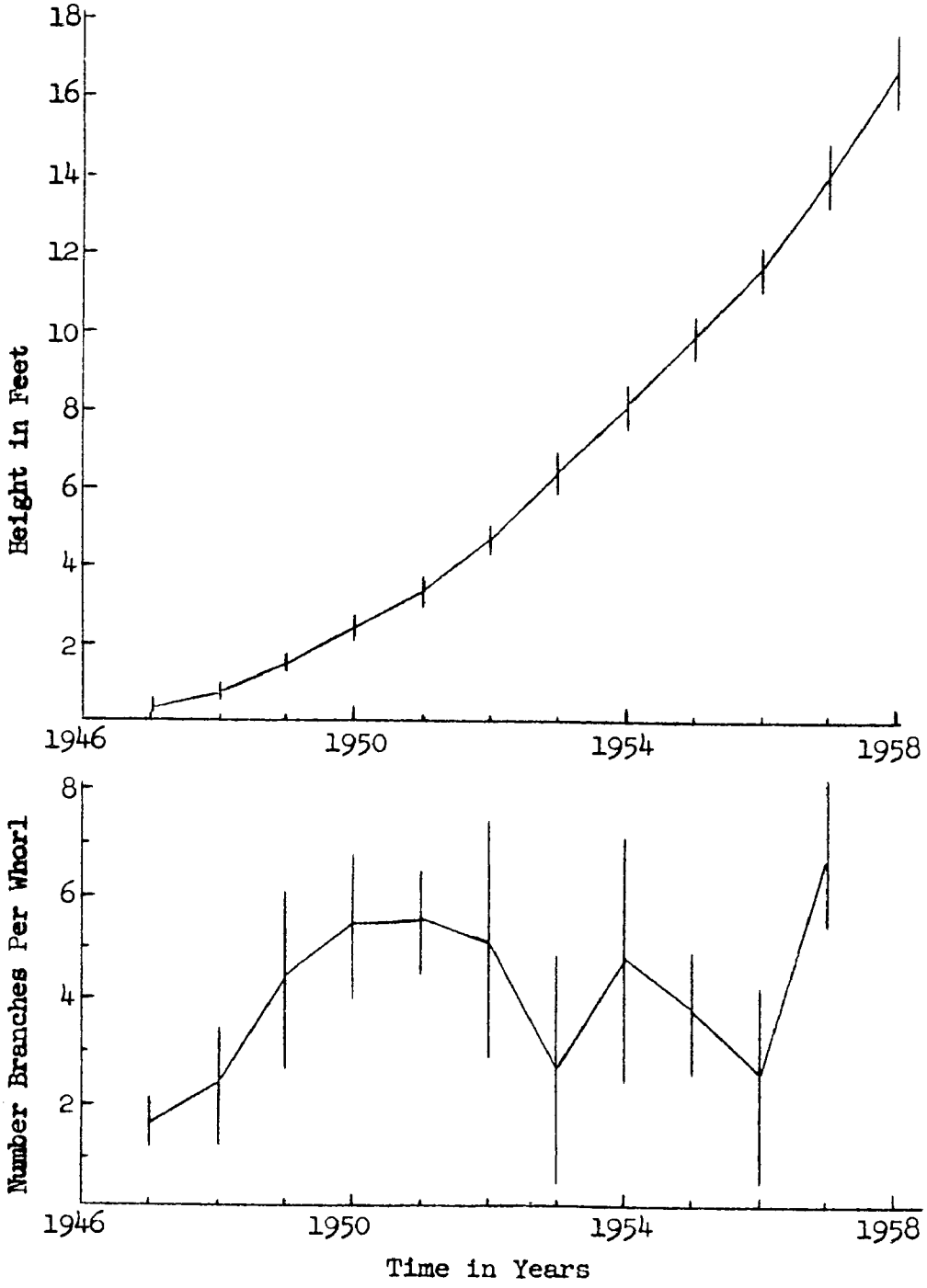


Fig. 14.--This red pine plantation in Wexford County, Michigan, was infested by the shoot moth for 9 years. Although no stem damage occurred, reductions in the number of branches per whorl occurred in certain years. Vertical bars show one standard deviation. (See Fig. 13, Above left)



Fig. 15.--Some red pine plantations have recovered from severe shoot moth attack. These plantations suggest that natural controls do exist and vary in time. Upper: red pine in the Stinchfield Forest of the University of Michigan severely damaged in 1946-47 (Washtenaw Co., Mich.). Lower: This is an area where Dr. W.E. Miller conducted his shoot moth studies (Miller and Neiswander, 1955). These trees were severely damaged, yet in 1955 normal height growth continued (near Waynesburg, Ohio).

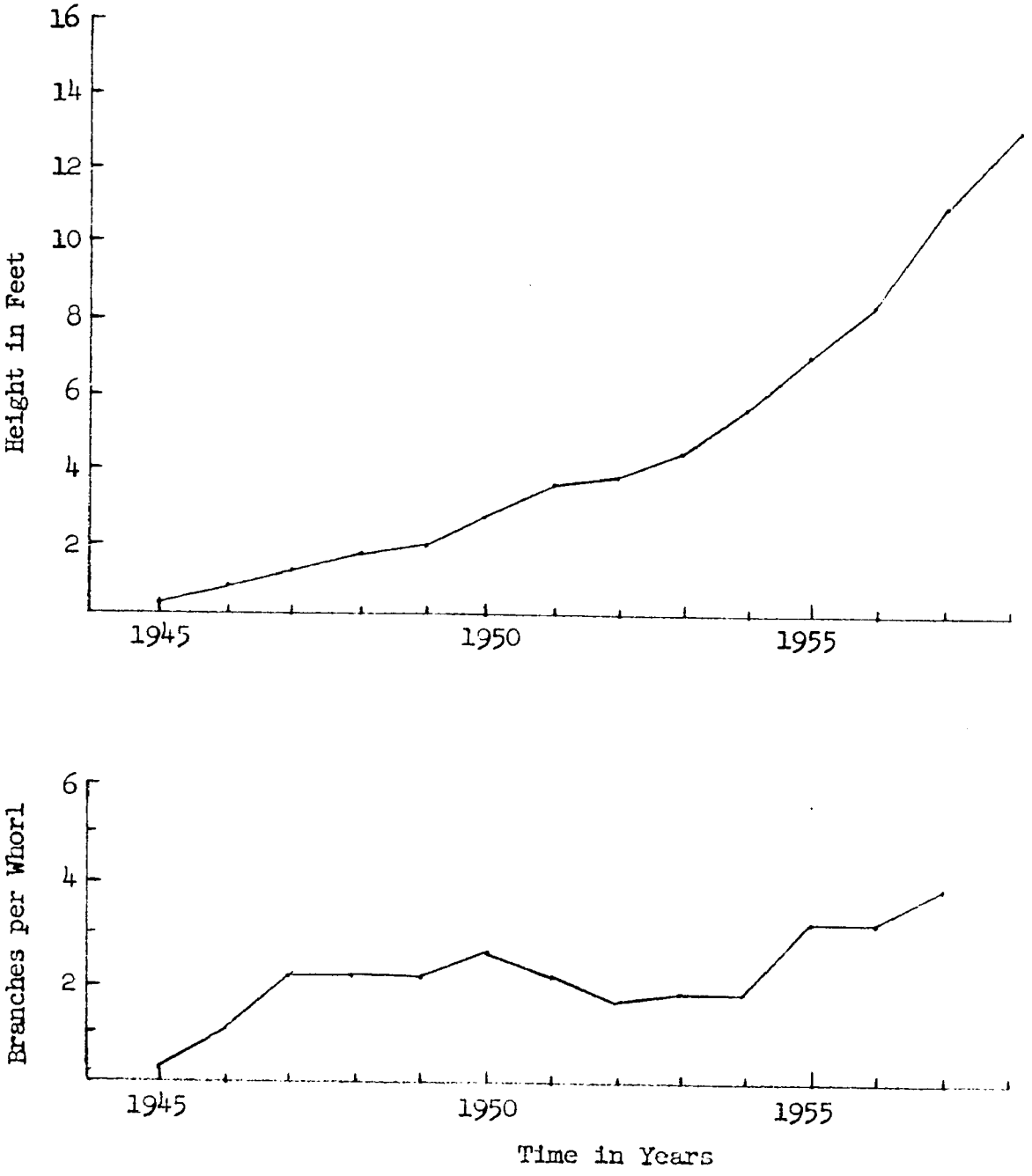


Fig. 16.--The red pine plantations where Miller and Neiswander (1955) conducted their studies have resumed normal height growth. Insecticide treated plots could not be distinguished from non-treated plots in the winter of 1958-59 (near Waynesburg, Ohio). Plantations which have recovered from a shoot moth outbreak supply the evidence that natural control factors vary in time. (See Fig. 15, lower)



Fig. 17.--These red pine were damaged by the first shoot moth outbreak in America. This plantation has remained infested since 1920. Following the 1930-33 outbreak, these trees have continued normal height growth. This plantation was described as an economic loss by Friend and West (1933, see Plates VI and VII). (Near New Haven, Conn.)

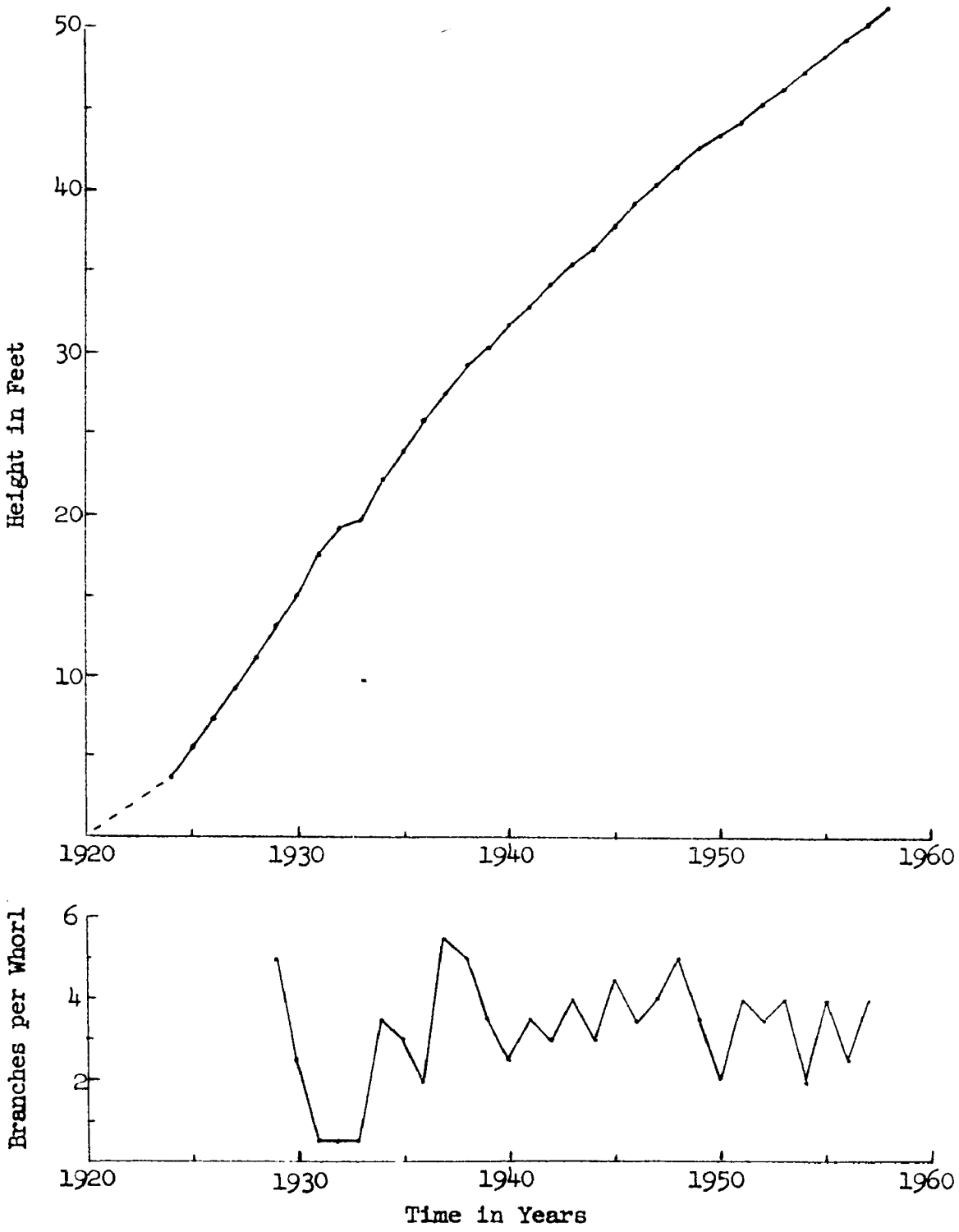


Fig. 18.--This plantation at Rose Pond (see Friend and West, 1933: Plates VI and VII) was seriously damaged by the shoot moth in the early 1930's. The insect was still present in 1958. The trees resumed normal height growth after the outbreak subsided.