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Ecological Changes Due to Thinning Jack Pine

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T. S. HANSEN[2]

INTRODUCTION

An examination of the rich and varied literature on "thinnings" shows that it is still one of the most controversial silvicultural practices. It is significant that many of the questions which gave rise to argument in the early days of forestry practice still find an important place in the literature on "thinnings". In spite of the years of painstaking work on this subject by foresters throughout the world, the questions of when to thin, how much to thin, and how often to thin are still without a definite answer.

Two explanations of this fact suggest themselves—the type of thinning studies carried on and the method of evaluating and analyzing the results. The usual thinning study consists of the establishment of a number of plots in a given stand, thinning them to different degrees or with different systems, and measuring the volume at the time of thinning and again at regular intervals. The thinning may be repeated at any of the intervals according to the system used or as the needs of the stand may dictate. Studies of this nature are necessary in all the various age classes and sites for any given species if a complete answer to the thinning problem is to be secured. These studies concern themselves with the results secured, as expressed in the growth of the stand, and do not look into the fundamental causes. The study of the environmental factors is usually entirely neglected, altho the cause of success or failure may often be found in the changes in these factors brought about by the thinning operation. The emphasis has been placed on the mathematical rather than the biological aspect.

It is not contended that studies of environmental changes will be necessary in all thinning plots. Sufficient studies should be made, however, to show how much these factors are altered by thinning practices. If, for example, it can be shown that changes in soil factors are most important, it may have an influence upon thinning practice by directing the attention to the creation of the optimum soil conditions. If

[1] The original manuscript covering this investigation was submitted as a dissertation in partial fulfillment of the requirements for the degree of Doctor of Philosophy at Yale University.

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the changes in some of the atmospheric factors are shown to be more important, thinning practices will strive to create the optimum in those factors.

The second cause of failure of past thinning studies to give a definite answer to the various questions lies in the method of interpreting and analyzing the data secured. Improved methods of computation and the application of statistical methods to the data have often altered conclusions drawn from earlier studies. Where complete records of past work exist, it has been possible to utilize the studies. All too often, however, old records are incomplete and it is impossible to recompute the values which are in doubt.

The studies of Carbonnier, Hesselman, and others in Sweden; Öelkers, Heck, Gerhardt, Schadelin, and others in Germany; Opperman, Möller, and others in Denmark, and Adams and others in this country indicate that there is a change in attitude towards the method of attack in thinning studies.

THINNINGS DEFINED

The variance of opinion on the function and purpose of thinnings is illustrated by the following definitions. The Committee on Terminology of the Society of American Foresters (1917) defines thinnings as "a cutting made in immature stands after the sapling stage for the purpose of increasing the rate of growth of those trees which are left". The emphasis is put on the increase in growth rate. Hawley (1935) defines a thinning as "a cutting made in an immature stand for the purpose of increasing the rate of growth of the trees that remain and the total production of the stand". In this instance the effect of the intermediate yield on the total yield is added to the increased rate of growth. An increased production not only in quantity but quality is implied. Schlich (1910) considers the need of the individual tree when he says, "Thinnings, then, are cuttings which have for their object to provide for each tree left standing, especially those that are to remain until the end of the rotation, that growing space which is best suited for its further development according to the objects of management."

PURPOSE OF THINNINGS

The early conception of the purpose of thinnings was that of increasing the total yield through a more rapid growth rate and through the utilization of material which if left would disappear before the end of the rotation. The more modern conception takes into consideration not only the quantity but also the quality of the product produced. Paul (1930, '32, '33) has shown by his recent studies that the quality of wood produced is influenced by the density of the stand. It is entirely feasible to control the density of the stand and thus produce wood of the desired characteristics. Schädelin (1934) suggests another value of thinning in that, through the elimination of undesirable individuals, the quality of subsequent generations of trees will be improved. He further maintains that the thinnings should not result in marked increase in growth rate, but should strive to maintain the most rapid rate of growth consistent with the quality of product desired. More and more the question of quality enters into the thinning problem.

HISTORY OF THINNINGS

It is difficult to get a clear conception of the development of thinning practice through a study of its history. In any individual country the development has been irregular and spasmodic; periods of progress have been followed by periods of return to old methods. Theories and practices have been presented as new only to be identified finally as practices of bygone days. Each country developed its practices independently, and it was not until comparatively recent times that any active interchange of ideas between countries made it possible for the application of foreign developments to be tried elsewhere.

Buhler (1922) in his Waldbau discusses the early history of thinning practice in Germany. As early as the fourteenth century some stands were recognized as being too dense for good development. The removal of dead, down, and unnecessary trees was practiced. The influence of this intermediate utilization on the total yield was recognized by the profession in the sixteenth century. That there was a difference in opinions even in that day, concerning the proper procedure, is indicated by the fact that Dobel in 1746 deplored the cutting of larger-sized trees in the thinning operation.

Schotte (1912) in an interesting article has shown the development of thinning practice in Europe from the earliest literature published by Carl van Fishbach in 1514 to the present time. He shows how the pendulum has swung from light thinnings at long intervals, as advocated by Hartig (1791), to the early and heavy thinnings of André and Liebach in 1832, and back to the practice of Heyer, who advocated thinnings as "early, often, and light". The German system was originally a thinning from below.

Denmark, under C. D. F. Reventlow (1800), developed an independent system which classified the trees as "useful", "neutral", and "harmful". "Useful" trees were given an opportunity to develop by removing the harmful trees at frequent intervals.

In France, thinnings from above were originally practiced until the German influence added thinning from below to the already established practice. In Sweden, thinning from below was the established practice until the Forest Experiment Station was established in 1902, when both thinning from above and below were used.

There is little to be said about the history of thinning in the United States. Most of the thinning work, up to the time the Emergency Conservation Work program was initiated, has been experimental in character and based largely on one of the European systems.

SYSTEMS OF THINNING

From the brief discussion on the history of thinnings, the impression might be gathered that the practical application of thinning in the forest is in a constant state of flux. This is apparently not the case. In actual practice systems are fairly well standardized and used.

In spite of the large number of thinning systems which can be found in forestry literature, each one claiming some distinct difference from all others, they all fall into three general classes: (1) The low thinning system, (2) the crown thinning system, and (3) the selection thinning system.

Such systems as Heck's (1931) free thinning and Schädelin's (1934) selection thinning are essentially combinations of the first two methods and do not represent any new principles in the selection of trees for removal.

In any system of thinning yet devised, the relative crown development of the tree is the basis for selection of trees for removal. Numerous systems have been developed for separating the trees of a given stand into crown classes. Some of these systems take into consideration only the relative crown development of the trees, while others include a description of the bole as well. Other systems seek to divide the stand into different levels and classify the trees of each level into crown classes.

The system advocated by the Committee on Terminology of the Society of American Foresters (1917) is based on the Kraft classification of 1844. The classes suggested by the Committee are: (1) Dominant, (2) codominant, (3) intermediate, (4) overtopped, (5) oppressed, and (6) suppressed.

This classification is simple, readily applied, and for the present economic conditions gives an adequate description of the stand. It is on the basis of this stand description that the various thinning systems are applied. The three thinning systems are so well known and understood that a discussion of them here does not seem necessary.

EFFECT OF THINNINGS

There are four variables in thinning practice which may influence the results. They are: (1) The age at which the thinnings start, (2) the interval between thinnings, (3) the number of trees removed, and (4) the crown class removed.

Schädelin (1934) has stressed the importance of beginning the thinnings at an early age. From a strictly technical standpoint, foresters in general are in agreement on this point. Very often economic conditions make it necessary to delay the operation. Where stands are differentiating themselves satisfactorily, very often this delay results in only a small loss. If the stand is dense, stagnation may set in and a loss in yield results.

The influence of the thinning interval on the yield has received very little attention. Carbonnier (1933) has described an experiment begun in Sweden for determining the influence of this variable. Möller (1931) believes that the ideal thinning, from a physiological standpoint, should be made annually. He maintains that the optimum conditions for growth occur in the middle of the interval between thinnings and believes that this condition can be maintained by annual thinning. He recognizes the economic impossibility of annual thinnings and accordingly recommends a short interval of two or three years, as used in Denmark, with a maximum of five years.

Both Möller and Carbonnier stress the influence of the thinning interval upon soil conditions. The effect of the increased light and heat upon the physical and biological characteristics of the soil have not as yet been completely studied.

The number of trees removed and the crown classes removed are more or less dependent upon the system and degree of thinning practiced. Carbonnier brings out the difficulty in comparing thinnings of different or like intensities because of a variation in the length of the interval between thinnings. Thus a thinning removing 20 per cent of the volume of the stand with a five-year interval would mean a 4 per cent volume removal annually, but with a ten-year interval the volume removed is only 2 per cent annually. The degree of thinning is equally important with the interval between thinnings, since upon the degree of thinning and the crown class removed depends the change in growing conditions within the stand.

A lack of agreement upon the effect of thinnings is evident in the present German literature. There is a considerable discussion concerning the so-called "Schnellwuchsbetrieb" which is essentially the application of the Danish thinning system to German stands.

Wiedemann (1929) contends that the total yield is not affected by the degree of thinning and that the effect of thinning on height and diameter growth has not yet been proven. Gerhardt (1930) takes the opposite view and bases his conclusions on observations of individual trees and upon Danish experience.

Guttman (1925), in his discussion of the spruce thinning plots established in Prussia in 1872, found that the "B" grade of thinning gave the best results. Kunze (1918) found that the "C" thinning was superior to lighter degrees in the Scotch pine stands of Saxony. He claims a greater height and diameter growth in the heavier degree of thinning.

In the United States many examples of experimental thinnings can be found. One of the earliest is the series of white pine thinning plots established by the U. S. Forest Service at Keene, New Hampshire, and taken over by the Yale Forest School in 1915. Hawley (1922-1927) states that, considering all factors, the heavy thinning is superior to the light thinning.

Korstian (1920), in working with western yellow pine stands of sapling age in central Idaho, found that diameter growth increased markedly as a result of thinning. Roeser (1922) found that diameter and height growth increased with the degree of thinning in the planted jack pine stands in Nebraska. The author (1929-1931) has found that heavier thinnings increased the growth in dense young stands of jack pine, but that in older less dense stands there was no effect.

Meyer (1931), in thinning nine-year-old stands of Douglas fir, found that thinning has a decided effect upon diameter growth but not on height growth. The age of the stand makes it doubtful whether or not the operation should be classed as a thinning or fall into one of the other stand treatment classes such as a cleaning.

No attempt has been made to cover the entire field of the literature upon the effect of thinning. The most prevalent opinion seems to be that thinning does increase the rate of growth and the total yield. If there are differences in results, it must be remembered that the forest is a living organism subject to constant variation.

ENVIRONMENTAL FACTORS

Practically all the factors of site are subject to change as a result of thinning practice. The degree of change will vary with the degree of thinning, the character of thinning, the type of stand involved, and the general climatic conditions. Very few studies have been made of the effect of thinning upon all of the site factors. Single factors have been studied, such as light or soil moisture, but it is only in exceptional cases that a complete study of factors has been attempted. Such a study was made by Adams (1930) and will be referred to from time to time. Carbonnier (1933) began a similar study in spruce thinning in Sweden in 1932.

The lack of such fundamental studies is probably due to the fact that so many other factors enter into thinning practices. One of the most powerful of these factors is the economic consideration. Usually it is necessary to subjugate all other factors to this one. Gerhardt (1930) feels that the thinning problem should be studied from the standpoint of volume. Wiedemann (1929) agrees that the volume study is important, but feels the necessity of ecological studies as well in order to arrive at a complete understanding. Möller (1931) stresses the physiological aspects in discussing thinnings.

Fernow (1916) stated that "Silviculture is the pivot of the whole forestry business." He gave as three reasons for the lack of silviculture in America: (1) Those inherent in nature, (2) those inherent in economic conditions, and (3) ignorance of foresters as to procedure. He advised silvicultural studies from a biological and ecological aspect as a basis for silvicultural practice.

There is a general agreement among foresters that ecological and physiological studies are essential. Some authorities feel, however, that economic and volume studies are of greater importance in determining the value of thinning. This is true enough, but, in the final analysis, in order to develop systems of thinning that may be tried out for their economic fitness, there must be an understanding of the principles underlying the practice.

In this study the following factors are considered: temperature, rainfall, evaporation, humidity, light, soil temperature, soil moisture, and humus conditions. There is a voluminous literature available as the result of the study of all these factors. No complete review of the studies of each factor will be made, but only such studies as seem pertinent will be discussed.

Temperature

Temperature has been considered by some authorities as the master factor of plant distribution. Merriam's (1898) theory of temperature zones is a good illustration of this, and there is much to be said in behalf of this theory. This dealt only with the distribution of a species, not with the functioning of a given species from a physiological standpoint within its range. Shreve (1915) and Pearson (1931) have shown that the altitudinal distribution of certain species of the southwest is controlled by temperature in the upper limits and by moisture in the lower limits. This brings out the complexity of the problem of correlating factors with growth and with distribution.

Toumey (1928) stated that air temperature directly affects growth. Jost (1907), however, regards temperature as an indirect influence serving as a stimulus to the plant. Actually they are in agreement upon the effect of temperature. Jost states that "All the vital processes in the plant take place within definite temperature limits." It is recognized that there are three cardinal points in the relationship of temperature to growth: a minimum, an optimum, and a maximum. In the case of plant distribution, the minimum and maximum points are the controlling factors. The optimum lies between these limits. This optimum has been determined for some of the lower plant forms, but as yet it has not been determined for tree species.

Lundegardh (1925) states that the optimal conditions for accumulation of carbohydrates in sun plants is a day temperature of 10° to 30° C. The significance of night temperature decreases towards the poles. He concludes that summer growth is closely tied up with temperature while spring growth is dependent upon reserve foods. He believes that the rate of growth changes with small changes in temperature, but gives no definite figures upon the rate of change.

Friederich (1897) was one of the first to study the effect of the various factors of environment upon growth. His dendrometers were probably not accurate, but he was able to draw some conclusions from his work. He concluded that temperature was not one of the most important factors. Hartig (1891), writing some six years previously, came to the conclusion that temperature was the most important factor in diameter growth of trees.

Schwarz (1899) reached the conclusion that the temperature of the months of January to March, inclusive, was correlated directly with growth. Heck (1931) was not able to correlate growth with temperature alone. Lodewick (1930), working with longleaf pine in Florida, was not able to show any effect of temperature on diameter growth. Baldwin (1931) found that height growth of some northeastern conifers did not begin until a weekly mean soil and air temperature of 50° F. had been reached. Pearson (1918), in studying height growth of western yellow pine saplings in Arizona, found that air temperature was not important except in its effect upon moisture conditions. Hiley and Cunliffe (1922), in studying thrifty young plantations of exotic conifers in England, found that current height growth seemed to rise and fall with temperature. They secured a higher degree of correlation with the maximum temperature than with the mean.

There is much conflicting data in the foregoing. It is altogether possible that there may be no conclusive answer to the effect of the temperature upon growth. The effect of temperature upon distribution, however, is understood and quite universally agreed upon. This factor is one that is often altered to a considerable extent by thinning practice.

Precipitation

Atmospheric precipitation is of importance to the tree only through its effect on soil moisture and humidity. From a silvicultural standpoint, the mechanical effect of snow and sleet storms is of importance. In this study, only the ecological or physiological aspect is considered. The water content of the soil in the early spring is derived from the late fall rains, winter snows, and early spring rains. When the soil is well supplied with moisture throughout the root zone in the spring, additional precipitation should have little effect upon the growth unless unfavorable conditions of too much moisture are created by it.

In interpreting the effect of precipitation, we find no agreement as to its effect upon growth. Douglas (1914) has worked out a correlation between diameter growth and rainfall in western yellow pine through which he has analyzed the climate of the past, established climatic cycles, and correlated these with the occurrence of sun spots. Robbins (1921), working with oak in Missouri, was not able to establish a definite correlation between precipitation and diameter growth.

Böhmerle (1905) showed the effect of drouth periods on diameter growth by an experiment in irrigation and by analyzing the growth of sample plots during the dry year of 1904. There was a general falling-off in growth with decrease in precipitation. Schwappach (1904) believed that the precipitation, first, and the temperature, secondly, influenced the rate of annual growth. He based his conclusion upon the growth analysis of 22 sample plots in 7 different localities of Germany.

Hesselman (1904) established definite correlation between height growth and precipitation during the latter part of the previous growing season. He found that diameter growth, however, was dependent upon precipitation of the current year. Pearson (1918) found that height growth of western yellow pine was dependent upon winter and spring precipitation. Lodewick (1930) found that the amount of precipitation occurring from March 16 to October 15 bore a definite relationship to diameter growth and that the amount of summer wood formed was in definite proportion to the precipitation.

Schubert (1931) in analyzing records of growth and rainfall was able to establish a definite relationship between rainfall during the growing season and growth in basal area. Whether or not his formula for working out the correlation was correct is open to some question.

In all probability the theory of limiting factors enters into the consideration of precipitation as well as temperature. It must be remembered that all the precipitation that falls does not become available to the tree. The amount varies with topography, vegetation, soil temperature, and other factors. At best the rainfall is only an approximate indication of the moisture that becomes available to the tree. Measurement made by Mitchell (1930) in Wisconsin showed that 78.5 per cent of the total rainfall reached the ground in a jack pine stand and 81.8 per cent in a hardwood hemlock stand. The amount reaching the ground was greater in the heavier storms.

There is much work to be done to arrive at definite conclusions as to the effect of rainfall on growth. From a physiological standpoint, we have the cumulative effect of the season's precipitation and the immediate effect of the storm. A dendrograph operated on a Norway pine tree at the Cloquet Forest Experiment Station showed a rapid increase in a relatively short time after a rainstorm followed by a decrease, varying in intensity with weather conditions. The increase never disappeared entirely. This would seem to indicate that not only the total precipitation, but its distribution must be taken into consideration.

The thinning operation can, of course, not alter the amount of precipitation that falls, but it can have an effect upon the amount that reaches the ground.

Relative Humidity

Relative humidity is in a sense itself not a factor of site. It is rather an expression of the result of a combination of factors. Changes in air temperature, occurrence of precipitation, wind movement, and solar radiation all affect the relative humidity. Weaver and Clements (1929) believe that relative humidity through its effect on transpiration is one of the most important factors. Other authorities have not been able to establish a definite correlation. Friederich (1897) found that relative humidity was closely associated with the growth of trees as measured by his dendrometer. Toumey (1928) felt that relative humidity is only of indirect biological importance and, because it gives an indication of evaporation, indicates the transpiration loss.

The well-known fact that the redwoods occur in the so-called "fog belt" in California indicates that at least in some instances relative humidity is an important factor in plant distribution. While definite proof of correlation is lacking, it seems reasonable that relative humidity would have some effect upon transpiration, and thus upon growth. Since relative humidity is the result of a combination of factors, it is probably more difficult to evaluate its effect.

Evaporation

Factors which influence the relative humidity may also influence the rate of evaporation. Some difficulty has been experienced in securing a satisfactory method of measuring evaporation when relating it to plant growth. The water loss through the leaf is controlled by the size of the stomatal opening. Stålfelt (1924), in studying the CO_2 assimilation in trees, found that there were two types of stomatal openings—a good-weather type and a rainy-weather type. In the first type, the stomata began opening at 6 a.m., reached a maximum at 8 a.m., closed in about an hour, and remained closed until the next morning. In the second type, the stomata opened later, never reached the maximum, but remained partially open for eight hours. No device has as yet been able to approximate the effect of this opening and closing of the stomata. Probably the most satisfactory is the Livingstone spherical atmometer. Briggs and Schantz (1917) found that this atmometer was more sensitive to wind changes than the plant and less sensitive to solar radiation.

Shreve (1915) has used the evaporating power of the air in combination with the available soil moisture to determine a "master factor" of site, apparently with some degree of success, in the arid regions of Arizona. Li (1926) found that atmospheric evaporation was reduced 2.8 per cent by grass cover, 22.8 per cent by the old forest, and 41.5 per cent by the young forest.

Unless actual transpiration measurements are possible, the evaporating power of the air seems to be the best method of evaluating the effect of the various factors upon transpiration.

Light

Light is indispensable for the formation of chlorophyll, and consequently for most of the physiological processes. It is not the only necessary factor and can not be singled out as such, since without adequate water, or temperature, growth ceases as readily as it does in the absence of light, possibly even more rapidly.

Zon and Graves (1911) state concerning light: "In the forest it largely determines the height growth of trees, the rate at which stands thin out with age, the progress of natural pruning, the character of the living ground cover, the vigor of the young tree growth, the existence of the several storied forest, and many other phenomena upon which the management of the forest depends." Since the time that this was written, much work has been done which has proven that light is not the only factor involved.

Plant physiologists in general agree that only a small percentage of radiant energy is used in photosynthesis. Burns (1923) and Grasovsky (1929) found that the minimum light requirement for white pine was 170 foot candles, which was less than the light intensity under the densest canopy. As in other factors, there exist three cardinal points —a minimum, a maximum, and an optimum.

Öelkers (1914) studied light conditions in thinned spruce and beech stands, measuring the light by means of radiometer carefully calibrated in the laboratory. He accounted for the increased growth through the increase in warm rays and even felt so convinced that his results were accurate that he predicted the amount of increased growth that would occur with varying increases in light intensity. All other factors were disregarded.

Shirley (1929) found that growth was proportional to the amount of light up to 50 per cent intensity, beyond that there was no correlation. Working under virgin Norway pine, he (1932) found that with a 5 per cent light intensity, no reproduction was established; at 17 per cent, fair reproduction; at 35 per cent, plus excellent. The maximum height growth for Norway pine occurred at 63 per cent light intensity, for jack pine at 75 per cent, and for white pine at 36 per cent. He concludes that 35 per cent of full sunlight is necessary for good growth, but that it is possible for trees to survive under much lower intensities.

Boysen-Jensen (1929), in studying the light requirement of Danish trees, found beech seedlings surviving at 0.25 per cent of full daylight, birch at 0.8 per cent, and ash at 0.5 per cent. He states that older trees require more light; beech, to thrive, needs 6 to 10 per cent light; birch, 20 to 30 per cent light.

Some of the benefit of increased light, which comes about through thinning, may be a difference in proportion of shade leaves and sun leaves developed. Boysen-Jensen states that sun leaves are much more efficient in greater light intensities than shade leaves. Aaltonen (1926) agrees with other authorities in judging that light is not the most important factor. He feels that the soil mass and nutrients are more important.

Summing it all up, there seems to be a general agreement that light is not generally a limiting factor. In thinning operations, however, the effect of the increased light on sun and shade leaves and its effect on the humus conditions are of importance.

Soil Temperature

The effect of soil temperature has been studied only slightly. Some work has been done on the effect of surface soil temperatures, but very little has been done on the effect of temperatures at deeper levels. Toumey and Neethling (1923) found that the increased survival occurring when seedbeds were shaded was due to decreased surface temperature. Bouyoucos (1916) states that there are two sets of factors which control soil temperatures: The intrinsic, which includes specific heat of the soil, heat conductivity, radiation, water content, evaporation of water, concentration of soil solution, topographic position, and condition of the surface; and the external, which includes meteorological elements. The effect of the intrinsic factors is passive, being influenced by the external.

From the above it can be readily concluded that soil temperatures in the forest would be quite different than in the open. The forest influences radiation, evaporation of water, concentration of soil solution, and the condition of the surface. It also alters to a greater or lesser degree the meteorological factors which affect soil temperature. The investigations of Li (1926), Toumey and Neethling (1934), and Mitchell and Zon (1929) bear out this conclusion. Two years of records on soil temperatures at the Cloquet Forest Experiment Station showed that the soil temperatures in jack pine type were about 2° F. above those in the Norway and white pine type and 8° to 9° F. above those in the swamp at 6-inch, 12-inch, and 24-inch depths. The temperatures in the jack pine type showed considerably more fluctuation than in the other two types.

Adams (1934) studied the effect of soil temperature upon the growth and development of white pine seedlings. Seedlings were grown under various constant soil temperatures, while other factors were kept practically constant. He found that with a mean soil temperature of 45° F. at an 8-inch depth, the germination period was 63 days, while with a mean temperature of 87° F. it was shortened to 11 days. The root growth was greater and the top-root ratio smaller with higher soil temperatures.

This study, like most soil temperature studies, was carried on with seedlings. Obviously at different ages a tree may need, or be able to endure, conditions which might not be favorable to it in the seedling stage. However, it is reasonable to suppose that soil temperatures that are favorable to the development of roots in the seedling will be favorable to root development in the more nearly mature tree. If thinning does appreciably increase the soil temperature, it should stimulate the root development.

Soil Moisture

The trees with which we work in this country must obtain the water necessary for all physiological functions from the soil. Here the complexity of the problem of relating the site factors to growth is brought out again. Fricke (1904) and later Toumey and Kienholz (1931) found that by trenching areas under a mature stand, thereby eliminating root competition, the entire make-up of the ground cover could be changed. Seedlings were able to establish themselves and grow under light conditions that were entirely prohibitive before the trench was dug. Pearson (1930) did not secure comparative results under Arizona conditions. On trenched plots under dense 30-year-old jack pine at Cloquet, the writer did not find any radical changes in ground cover, nor was there any reproduction established, altho seed trees of Norway pine, jack pine, and black spruce were located close enough to serve as a source of seed. It would seem from this that various combinations of factors may have entirely different results. Under one set of combinations soil moisture might easily be the limiting factor, under another set light or some other factor, the limiting one.

Conrad and Veihmeyer (1929) found that the distribution of water throughout the soil was not uniform, but was dependent upon the root concentration. Variations in the character of the soil, the surface litter, and slight topographical variations may also cause uneven distribution of soil moisture. The character of the forest and its density will have an appreciable effect upon the soil moisture and its distribution. Craib (1929) found that "during the driest part of the year there is more than twice the volume of water available to plants in the first 90 cm. of soil in the open than there was in the forest."

It seems logical to suppose that, if the amount of soil moisture is influenced by the forest, a reduction in the number of stems, such as results from a thinning operation, would result in a reduced consumption of soil moisture and be reflected in a higher moisture per cent in the soil. Albert (1915) studied the effect of thinning on soil moisture on poor pine soils. He found that the thinned plots showed a higher moisture per cent at 20-centimeter and 40-centimeter depths than the unthinned; on plots where the slash was left and scattered, the soil moisture was still higher. The advantage of the thinning and slash over the unthinned was computed to be the equivalent of nine liters per square meter for the growing season.

Humus Conditions

Möller and Carbonnier stress the importance of the character and condition of the humus in its relationship to growth. They contend that by correct thinning, raw humus formation can be prevented, nitrification speeded up, thereby increasing the plant food available. Hesselman (1925) agrees with them in this contention. No attempt will be made to review the literature on this subject, since the present study is concerned with this phase of it only in a very elementary way.

PURPOSE OF THE STUDY

The purpose of this study is to analyze the site factors on two areas thinned at different degrees and compare them with the unthinned, to determine by this method which of the factors shows the greatest change and possibly had the greatest effect upon the growth rate, and to correlate, if possible, at least some of these site factors with the growth. The individual trees have also been analyzed, both from the standpoint of volume growth and from crown and needle development. From this information, it may be possible to direct the attention to that factor which influences growth to the greatest degree and to the class of tree that shows the greatest response. It should serve as a basis for practical and proper thinning methods.

JACK PINE

This study concerns itself only with jack pine *(Pinus banksiana* Lamb). Gray (1908) calls jack pine "northern scrub pine" and describes it as "a low tree usually 5-10 (rarely 20) m. high. Found on barren, sandy or rocky soils. Nova Scotia to northern New York, west to northern Illinois, Minnesota and northward." While this description doubtless fits the tree as it occurs in New England, it is not applicable to the tree found in the western and northwestern portion of its range. Sterret (1920) gives a similar range and states that its east and west range is 2,500 miles and its north and south extension is 1,600 miles. With such a wide range, it naturally would show a wide variation in form. In Minnesota, trees 80 to 100 feet in height and 12 to 16 inches in diameter are not uncommon. The largest jack pine cut on the Cloquet Forest Experiment Station was 26 inches in diameter at breast height and 80 feet tall.

That it is an important commercial species is shown, in a measure, by the price that it commands on the market. Table 1, taken from U. S. D. A. Statistical Bulletins by Steer (1931-32-33) gives the price range for various years in Minnesota.

Table 1. Stumpage and Log Prices for Minnesota for Jack Pine and All Softwood Species

Year	Jack pine — Average price — Stumpage	Jack pine — Average price — Logs	All softwood species — Average price — Stumpage	All softwood species — Average price — Logs
1928	$2.00	$20.97	$2.43	$18.21
1929	2.23	18.47	4.57	22.49
1930	3.83	26.97	2.60	25.07
1931	3.88	17.63	5.16	21.45
1932	2.11	10.03	1.52	13.31

An inspection of the figures in Table 1 shows that jack pine averages well with the other commercial softwood species in Minnesota. Crocker (1926) estimated that in 1925 there were 41,000,000 cords of jack pine available in the Lake States, with an annual consumption of 141,178 cords for all purposes, of which 101,819 cords were pulpwood. The increasing utilization of this species for pulpwood is shown by the fact that the 1920 consumption was 40,000 cords for this purpose. He estimates the growth to be 1,000,000 cords annually, roughly seven times the annual consumption of that time.

Jack pine finds its largest use as pulpwood. In certain localities it is used for mine timbers, railroad ties, and often for boxboards. Sterret (1926) states that "In the Lake States jack pine produces chiefly small-sized, knotty lumber, much inferior to that from the Norway and white pines." It has been the writer's experience in delivering logs of these species to the mills at Cloquet that there was a difference of only five dollars per thousand board feet between jack pine and Norway and white pine.

Jack pine has much to recommend it to foresters. It reproduces easily. The serotinus cones supply an ever-present source of seed. It begins to produce viable seed at an early age. Instances have been noted where four-year-old stands reproduced themselves following destruction by fire. It has a fairly rapid rate of growth and is adapted to rather poor sandy soils. The persistance of the limbs and its tendency to poor form can often be overcome by proper silvicultural measures such as thinning and pruning.

In comparison with white pine, according to tables by Gevorkiantz (1930), we find the jack pine has a considerably higher mean annual growth in cubic feet up to 30 years and that this difference is more marked on the poorer sites. The mean annual growth culminates at from 35 to 40 years in jack pine and at 70 years in white pine. Jack pine is a tree adapted to short rotation and to the production of small-sized products. It is altogether probable that the culmination of the mean annual growth can be delayed by thinning and the total yield and the size of the tree increased.

PREVIOUS THINNING WORK

Very little work has been done on the effect of thinning in jack pine. The writer, together with R. M. Brown (1929), studied a thinning in this species made on the Cloquet Forest in 1912. The stand was 37 years old at the time of thinning and showed no response to the thinning. Two factors were responsible for this. In the first place, the stand was probably too old to respond to a thinning from below, and, in the second place, it was slightly below normal density before being thinned.

The thinning plots of this study were reported upon by the writer (1931) at the end of the first five-year period. Considerable response was secured as the result of thinning this 27-year-old stand. The results will be discussed in detail later.

Roeser (1932), in studying thinning in planted jack pine in the Nebraska Sand Hills, found that early and heavy thinnings were to be recommended. One of the chief considerations in this instance was the conservation of the soil moisture through the reduction in number of stems. The work already done by him indicated that heavy thinnings were expected to yield 39 per cent more volume than unthinned at the end of the rotation.

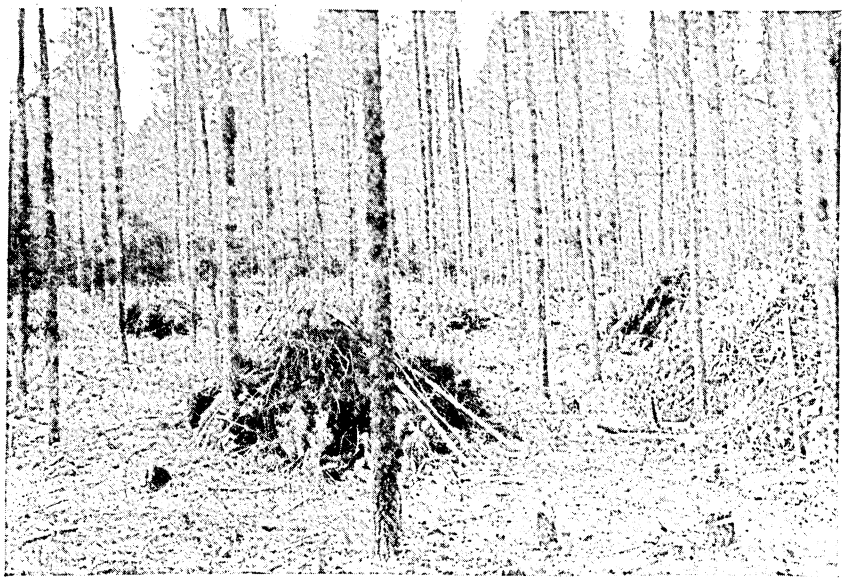

FIG. 1. VIEW OF THE HEAVILY THINNED PLOT IMMEDIATELY AFTER THINNING

Adams (1928), in studying the effect of spacing in a jack pine plantation, found that root competition retarded the diameter growth before it did height growth. He recommends that thinnings be made in jack pine plantations when competition sets in and diameter growth begins to be retarded.

DESCRIPTION OF THE STAND

The stand in which the plots are located is a rather dense uniform stand 37 years old. Fire scars upon large Norway pines adjacent indicate that it originated following a fire occurring in 1894, probably in the fall. The resulting reproduction was dense and uniform, varying from 1,000 to 4,000 stems per acre and averaging 2,000 stems per acre over the entire area. The ground cover consists of blueberry *(Vaccinium pennsylvanicum* Lam), wintergreen *(Gaultheria procumbens* L.), sweet fern *(Myrica asplenifolia* L.), trailing arbutus *(Epigea repens* L.), honeysuckle *(Lonicera canadensis* Marsh), northern brake fern, strawberry *(Fragaria americana* Britton), aster *(Aster sp.),* false lily of the valley *(Maianthemum canadense* Desf.), false Solomon seal *(Smilacinia racemosa* L.), fireweed *(Epilobium angustifolium* L.), and pyrola *(Pyrola minor* L.). Underbrush such as hazel *(Corylus sp.),* alder *(Alnus sp.),* and willow *(Salix sp.)* is absent except in the small openings.

In the unthinned portions of the stand, there is a heavy mat of needles and mor, usually about two to three inches thick. The presence of mycelia in the lower portion of the mor indicates a tendency to the formation of raw humus.

The soil is a light, deep sand classed as "Omega" sand, decidedly acid in reaction. While there is no uniform layer of podsol, here and there throughout the stand spots can be observed where the gray horizon shows that some leaching has taken place. There is as yet no definite hardpan formation.

The annual precipitation varies from 25 to 30 inches and for the growing season (April 15 to September 15) is usually about 14 inches. The mean temperature for the growing season is 55° F. Killing frosts may occur during any month of the year, but the normal frostless season is from June 15 to September 1. The winters are long and severe, with heavy snowfall.

The height of average dominant trees shows that this stand falls in the 50-foot site index class, according to the yield tables by Wackerman (1925).

One thinning plot, together with the check plot, was established in the fall of 1925, the second plot was established early in the spring of 1926. While they were established in different years, the number of growing seasons is entirely comparable.

DENSITY OF THE STAND

Before thinning, Plot 1, the heavily thinned plot, had 2,478 trees per acre with a basal area of 105.425 square feet. Compared with the stand in the normal yield table, it was overstocked in number of trees by 31 per cent but the basal area was normal. Competition had, of course, set in long ago. The average diameter was 2.8 inches, which is 0.4 inch below the yield table normal.

Plot 2, the moderately thinned plot, had 2,230 trees per acre, with a basal area of 103.023 square feet. Compared with the normal yield table, there were 18 per cent too many trees, while the basal area was 2 per cent below normal. The average diameter was 2.9 inches, which is 0.3 inch below normal. This portion of the stand also showed the effect of crowding.

The check plot had 3,040 trees per acre, with a basal area of 95.328 square feet. Compared with the normal yield table, there were 60 per cent too many trees and the basal area was 10 per cent below normal. The average diameter was 2.4 inches, which is 0.8 inch below normal.

Unfortunately, the check plot was overstocked to a greater degree than the two thinning plots. A small test area before establishment gave approximately the same density, the entire plot not measuring up to the sample, but since it was the best available, it was retained as a check plot.

Plot 1 covered an area of ½ acre and was surrounded by a control strip 33 feet wide. Plot 2 had an area of 0.4 acre and was surrounded by a similar control strip. The check plot covered an area of 0.25 acre and had a control strip of the same width as the thinned plots. They were all located within a radius of 100 yards, Plot 1 and the check being almost contiguous, Plot 2 lying at a distance of about 100 yards. Plot 1 and the check were level, while Plot 2 was slightly rolling.

DEGREE OF THINNING

At the time the thinning plots were established, normal yield tables were not yet available for jack pine. Consequently no effort could be made to reduce the stand to a normal yield table basis, either in basal area or number of trees. In Plot 1, which would be classed as a grade "D" thinning, an effort was made to leave 700 trees per acre. This is 130 more than the normal yield table gives for trees 4 inches DBH and over at that age. In Plot 2, an effort was made to leave 1,200 trees per acre, which is slightly more than double the number the yield table gives for trees 4 inches DBH and over. This thinning would be classed as a "B" grade.

For convenience in marking the area for thinning, it was divided into chain square units. The trees selected for leaving were marked with white paint. An effort was made to leave the thrifty dominants, well crowned, of good form, and free from disease. Since a fairly continuous crown cover is necessary to keep out hazel and alder, which prevent natural reproduction, considerable attention was paid to the spacing. This necessitated the leaving of some intermediate trees. The trees left were measured at the DBH point (4.5 feet above ground) with a diameter tape to the nearest 0.1 inch. The point was marked with paint and the tree was numbered with a zinc tag attached 6 inches above the point of measurement. Heights of 10 trees of each diameter class were measured by means of a Forest Service Standard Hypeometer. From these data a "height on diameter" curve was constructed. It is recognized that it would have been desirable to measure the heights of all the trees. Because of the density of the stand, which made it impossible to see the tops, this was not possible. Any error introduced by this method is probably consistent between the plots and between the subsequent remeasurements.

In Plot 1, 768 trees per acre were left. This was 31 per cent of the original stand. The thinning operation removed 69 per cent of the number of trees and 56 per cent of the volume. After thinning, the diameter of the average tree was 3.3 inches as contrasted to 2.8 inches before. The height of the average tree increased from 22.7 feet to 28.8 feet after thinning. The thinning reduced the number of trees to 40 per cent of the number in the normal yield table and the basal area to 43 per cent of the normal, while the average diameter was 0.1 inch above normal.

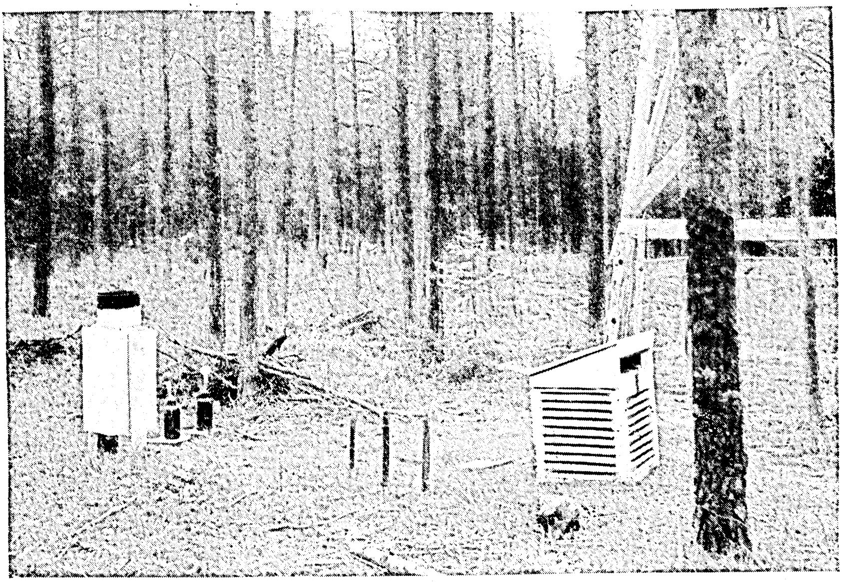

FIG. 2. VIEW OF THE HEAVILY THINNED PLOT TEN YEARS AFTER THINNING
Surface station for recording data is shown in the foreground.

In Plot 2, 1,105 trees per acre were left. This was 50 per cent of the original stand. The thinning operation removed 50 per cent of the number of trees and 33⅓ per cent of the volume. The height of the average tree was raised from 22.7 feet to 29.4 feet by the thinning. The thinning reduced the number of trees to 58 per cent of the normal number and the basal area to 65 per cent of the normal. The average diameter was 0.2 inch above normal after thinning.

In each instance the thinning was severe enough so that the growing space of the remaining trees was considerably enlarged.

EXPRESSION OF DOMINANCE

Deen (1933) found that the standard deviation of diameter at breast height was a satisfactory criterion of the expression of dominance in stands of like age. The expression of dominance is the result of the uneven rate of growth of individuals. This is, of course, the normal development of the stand. Where this differentiation is too great, it indicates the presence of trees that are apt to become wolf trees producing poor-quality material and in general reducing the yield. Thinnings can either increase or decrease the expression of dominance, depending upon the method of thinning used.

To be thoroly useful, a study of the expression of dominance should cover a complete range of site and age classes for a given species. While this is not available for jack pine, the standard deviation of diameters will provide a basis of comparison between the three plots at the time of the three measurements. The standard deviation of diameters, breast high, in inches is given in Table 2.

Table 2. Standard Deviation of Diameter Breast High, in Inches, for the Three Plots

Plot	1924	1930	1934
Check	0.81	0.90	0.83
Heavily thinned	0.83	0.92	1.07
Moderately thinned	0.72	0.86	1.03

Table 3. Comparison of Plots at the Five- and Ten-Year Periods

	Check	I Heavily thinned	II Moderately thinned
Age in 1925	27	27	27
No. of trees per acre			
1925	3,020	768	1,105
1930	2,464	762	1,097
Loss 1925-30	556	6	8
1934	1,980	748	1,069
Loss 1930-34	484	14	28
Basal area per acre, sq. ft.			
1925	81.11	46.39	68.73
1930	91.70	69.46	87.10
1934	113.38	87.57	103.22
Average diameter, inches			
1925	2.2	3.3	3.4
1930	2.6	4.1	3.8
1934	3.2	4.6	4.2
Average height, feet			
1925	22.6	28.6	29.8
1930	26.7	30.3	31.3
1934	29.4	33.4	33.1
Volume per acre, cu. ft.			
1925	1,436.8	767.9	1,125.0
1930	1,808.0	1,175.7	1,514.6
1934	1,969.9	1,548.9	1,862.7
Volume loss per acre, cu. ft.			
1925-1930	124.4	4.66	6.95
1930-1934	144.9	7.00	15.25
Volume increase per acre, cu. ft., without loss			
1925-1930	371.3	407.8	399.6
1930-1934	261.9	373.0	348.1

An inspection of these deviations shows that Plot 2, the moderately thinned plot, was suffering the most from stagnation, since it has the lowest standard deviation. The effect of thinning is not so noticeable at the first remeasurement; the differentiation is nearly the same in each case. The difference is more marked at time of the second remeasurement, the size of the standard deviation varying with the degree of thinning. Evidently the trees had more time to adjust themselves and take advantage of the increased growing space during the second five-year period. The fact that the thinning operation did not materially change the expression of dominance indicates a very uniform stand and that the thinning operation was not entirely a low thinning.

Table 4. Comparison of Equal Number of Crop Trees at the Five- and Ten-Year Periods

	Check	I Heavily thinned	II Moderately thinned
Age in 1925	27	27	27
No. of trees per acre			
1925	600	600	600
1930	600	600	600
Loss 1925-30	....	....	....
1934	600	600	600
Loss 1930-34	....	....	....
Basal area per acre, sq. ft.			
1925	35.10	41.41	47.22
1930	48.75	62.74	63.15
1934	57.56	79.01	78.77
Average diameter, inches			
1925	3.3	3.6	3.9
1930	3.9	4.4	4.4
1934	4.2	4.9	4.9
Average height, feet			
1925	28.9	29.7	30.8
1930	32.6	31.5	34.2
1934	34.4	33.9	35.6
Volume per acre, cu. ft.			
1925	574.4	683.4	829.7
1930	847.1	1,067.2	1,134.9
1934	1,036.0	1,412.1	1,436.9
Volume loss per acre, cu. ft.			
1925-1930	....	....	....
1930-1934	....	....	....
Volume increase per acre, cu. ft., without loss			
1925-1930	272.8	383.8	305.1
1930-1934	188.9	344.8	302.1

VOLUME GROWTH

It is usually customary to fell sample trees to determine the volume of the various thinning plots. In this instance, volumes were computed by Table 23 as given by Sterret (1920). This table was found to be applicable and by using it alike in each instance, any error introduced

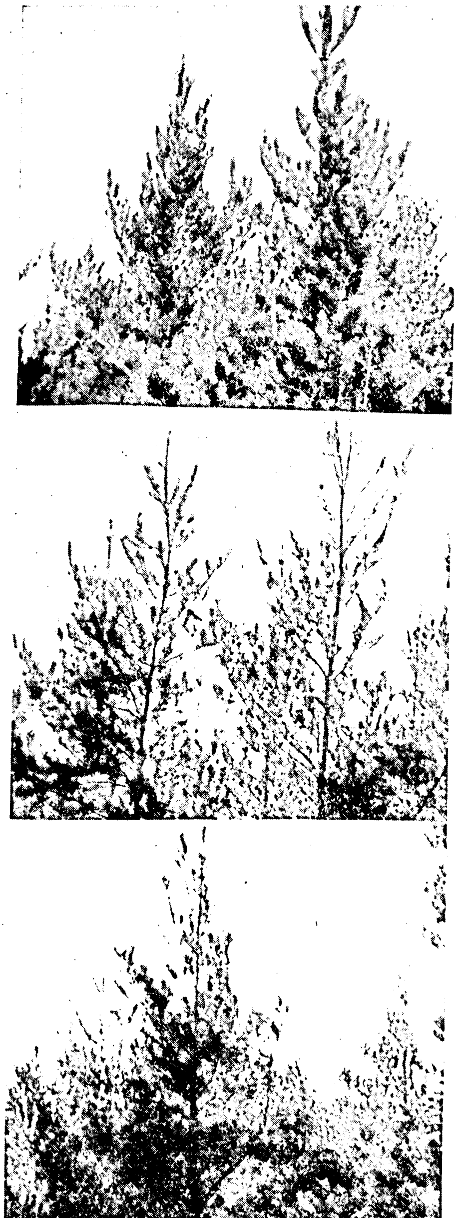

Fig. 3. Top, Crown Development of Heavily Thinned Plot; Middle, Moderately Thinned; Bottom, Unthinned

would be constant. At the time of the 1934 remeasurement, three trees of each crown class were felled and analyzed. The study of these trees will be referred to later.

Table 3 gives the growth in basal area, diameter, height, and volume on the tree plots during the ten-year period since they were thinned.

Any variation in this table from the figures previously reported by the writer is caused by an increase in the accuracy of volume computation. In addition, a few wolf trees occurring in the check plot have been eliminated from the computation.

In the check plot the diameter of the average tree increased from 2.2 inches to 2.6 inches during the first five-year period and from 2.6 inches to 3.2 inches in the second five-year period. It must be remembered that this diameter increase is not entirely the effect of growth. There was a loss of 556 trees per acre during the first five-year period and a loss of 484 trees per acre during the second period. Since these trees were mostly in the smaller size classes, it would automatically tend to raise the diameter of the average tree. The height of the average tree, also influenced by the loss in numbers, increased from 22.6 to 26.7 feet in the first five-year period and to 29.4 feet in the second five-year period. There was a volume increase of 371.3 cubic feet during the first five-year period and of 261.9 cubic feet during the second. Consideration must also be given to the 124.4 cubic foot loss during the first period and to the 144.9 cubic foot loss during the second period, in arriving at the actual volume growth.

In comparison with the normal yield table, the total height of the average tree of the unthinned stand was 10 feet below normal at the ten-year measurement. The diameter of the average tree was 1.2 inches below normal. The basal area was approximately 3.4 per cent below normal. The number of trees per acre was 83 per cent above normal. The total volume was 26 per cent below normal. The mean annual increment was 74 cubic feet during the second five-year period; the normal at 37 years is 72 cubic feet. If the volume loss be added, the increment becomes 99 cubic feet for the first period and 81 cubic feet for the second period. This comparison with the normal shows that the crowding had some effect on the average height and diameter but very little on the yield.

Plot 1, the heavily thinned plot, showed an average diameter increase from 3.3 inches to 4.1 inches during the first five-year period and to 4.6 inches during the second five-year period. In this plot the increase is largely the result of growth, since the loss in numbers was slight. The height of the average tree increased from 28.6 feet to 30.3 feet during the first five-year period and to 33.4 feet during the second five-year period. The volume increment for the first five-year period was 407.8 cubic feet and for the second 373.0 cubic feet. The loss in volume was only 4.66 cubic feet in the first period and 7.00 cubic feet in the second.

In comparison with the normal, at the ten-year remeasurement the average tree of the heavily thinned stand was 6 feet below normal in height. The diameter of the average tree was 0.2 inch above normal. The basal area was 25 per cent below normal. The mean annual increment for the first five-year period was 81 cubic feet and for the second 74 cubic feet, the normal at 37 years being 72 cubic feet. The comparison with the normal shows that in spite of the smaller number of trees, the mean annual increment is maintained, indicating a more rapid rate of growth due to thinning.

In Plot 2, the moderately thinned plot, the average tree increased in diameter from 3.4 inches to 3.8 inches during the first five-year period and to 4.2 inches during the second five-year period. The height of the average tree increased from 29.8 feet to 31.3 feet during the first period and 33.1 feet during the second period. The loss in number was so small that it would have little effect upon the average. The volume increment for the first period was 399.6 cubic feet and for the second period 348.1 cubic feet.

In comparison with normal, at the ten-year remeasurement the average tree of the moderately thinned stand was 6 feet below normal in height, the diameter was just normal. The number of trees was approximately normal. The basal area was 12 per cent below normal. The total volume was 30 per cent below normal. The mean annual increment was 79 cubic feet for the first period and 69 cubic feet for the second, the normal being 72 cubic feet. The comparison with the normal brings out the effect of the previous overcrowding and the fact that the thinning has stimulated the increment.

In comparing the three plots, no growth per cents are given since they do not give a true comparison, being based on a varying volume for each plot. The heavily thinned plot showed the largest increase in diameter and the largest increment, if loss is not taken into consideration. The advantage in increment is not so great as might be expected, but the difference in number of trees must be taken into consideration.

A fairer basis of comparison than the total number of trees would be the growth on what might be considered the crop trees. On the Cloquet Forest jack pine will be grown on a 50-year rotation. This is slightly past the culmination of growth in the yield table but gives a more desirably sized tree. At this age there are 635 trees on the 50-foot site index in normal unthinned stands. Enough trees were selected from the largest diameters in each plot to make 600 per acre, such as might be expected to survive to the end of the rotation. Any forest owner would naturally be more interested in the growth rate of the trees which make up the final cut. Table 4 gives this comparison. The data in Table 4 show more clearly the advantage of the heavily thinned plot over the moderately thinned and unthinned plots. In this instance the chief interest centers around the total volume and the increment. The two thinned plots are above the check in volume. In increment, the heavily thinned plot exceeded the check by 111 cubic feet per acre during the first period and 156 cubic feet during the second period.

It is recognized that if these stands had been thinned earlier, and at short intervals, even better results might have been secured. The heavily thinned plot probably had too severe treatment, since in one thinning it was reduced nearly to the number of trees expected in a normal unthinned stand at the end of the rotation.

Table 5 gives an analysis of the growth of the trees by inch classes. The classification given in this table is the diameter breast high of the tree in 1925. Only the trees surviving in 1934 are included in this table. It serves to show how the various diameter classes grow during the ten-year period following thinning.

Probably the most significant comparison that can be made in Table 5 is in the diameter growth. The heavily thinned plot shows a much larger diameter growth than the moderately thinned and unthinned plots. In Plot 1, the two-inch class increased 0.5 inch during the first five-year period and 0.3 inch during the second; while in the moderately thinned the increase was 0.2 inch during the first period and 0.2 inch during the second period; in the unthinned the increase was 0.3 inch for the first period and 0.1 inch for the second. The same

Table 5. Analysis of Trees Surviving in 1934, by Diameter Classes

Diameter class	Number trees per acre				Per cent loss or gain	Average diameter, inches			Volume per acre, cubic feet						Increment, cubic feet per acre				Period growth, per cent	
	1925	Per cent total	1934	Per cent total		1925	1930	1934	1925	Per cent volume	1930	Per cent volume	1934	Per cent volume	1930	Per cent increment	1934	Per cent increment	1925 to 1930	1930 to 1934
CHECK																				
1	700	23.6	32	1.8	− 96	1.4	1.6	1.7	17.44	1.5	22.60	1.3	23.24	1.2	5.16	1.3	0.64	0.3	29.8	0.28
2	1,412	46.5	556	28.3	− 60.8	2.2	2.5	2.6	405.76	34.5	549.88	33.1	621.00	31.3	45.11	12.0	71.22	22.9	11.1	13.0
3	756	25.5	808	40.7	+ 6.9	2.9	3.4	3.7	547.88	46.4	789.00	47.4	967.96	49.4	241.22	62.4	178.96	57.3	43.0	22.6
4	140	4.4	452	22.7	+ 222.0	3.9	4.6	5.0	196.24	16.7	286.60	17.4	344.36	17.3	90.36	23.4	57.76	18.7	46.0	21.0
5	4	0.1	128	6.5	+3,100.0	5.2	5.9	6.2	10.48	0.9	14.12	0.8	16.64	0.8	3.64	0.9	2.52	0.8	34.8	17.9
Total	3,012	100.0	1,992	100.0					1,177.80	100.0	1,662.20	100.0	1,973.20	100.0	385.49	100.0	311.10	100.0		
PLOT I, HEAVILY THINNED																				
1	4	0.5	....	....	− 100.0	1.5	2.9	3.2	0.48	0.08	1.40	0.1	1.76	0.1	0.92	0.2	0.36	0.1	....	....
2	148	19.3	28	3.7	− 87.6	2.3	2.8	3.1	61.16	8.2	92.26	7.9	108.48	7.2	31.10	7.5	16.22	4.4	50.8	17.6
3	388	50.6	104	13.9	− 73.0	3.1	3.8	4.3	310.68	41.1	495.40	42.6	662.92	43.0	184.72	44.7	167.32	46.0	59.5	34.8
4	176	22.8	274	36.6	+ 56.0	3.9	4.8	5.4	248.22	32.8	379.50	32.5	512.40	33.6	131.28	31.8	132.90	36.4	53.0	35.0
5	42	5.5	210	28.4	+ 400.0	4.9	5.9	6.5	99.14	13.0	146.82	12.4	183.48	11.9	47.68	11.5	36.66	10.0	48.0	25.1
6	10	1.3	130	17.4	+1,200.0	5.9	7.0	7.7	34.18	4.6	52.00	4.5	63.18	4.2	17.82	4.3	11.18	3.1	52.0	21.5
Total	768	100.0	746	100.0					753.86	100.0	1,167.38	100.0	1,532.22	100.0	413.52	100.0	364.64	100.0		
PLOT II, MODERATELY THINNED																				
2	215	18.7	72	6.8	− 66.5	2.3	2.5	2.7	86.07	7.8	103.07	6.9	116.12	6.2	17.07	4.4	13.05	3.5	19.8	12.7
3	515	44.5	307	29.3	− 40.0	3.1	3.3	3.7	430.27	39.0	557.80	37.3	693.87	37.0	127.53	32.5	136.07	36.8	29.8	25.0
4	362	31.5	342	32.5	− 5.7	4.0	4.5	5.1	443.85	40.2	621.95	41.5	792.15	42.6	178.10	45.4	170.20	46.0	41.0	27.4
5	57	4.9	222	21.2	+ 293.0	4.9	5.6	6.1	126.80	11.5	186.87	12.5	233.92	12.5	60.07	15.2	47.05	12.5	47.8	25.0
6	5	0.4	106	10.2	+2,005.0	5.9	6.8	7.4	16.95	1.5	26.90	1.8	31.65	1.7	9.95	2.5	4.75	1.2	58.5	17.6
Total	1,151	100.0	1,049	100.0					1,103.94	100.0	1,496.59	100.0	1,867.71	100.0	392.72	100.0	371.12	100.0		

ratio applies in the three-inch class, while the difference is not so marked in the upper classes. The larger diameters lie mostly in the upper crown classes which are not crowded to the same degree as are the lower classes, and consequently do not show the response to thinning that the lower classes do. In the heavily thinned plot, the three-inch trees have the largest growth per cent, while in the unthinned, the four-inch, and in the moderately thinned, the five-inch and six-inch have the largest growth per cent. It is of interest to note the change in diameter classes. In the unthinned almost half the stand was composed of two-inch trees in 1925. By 1934 the three-inch trees had increased from 25 per cent to 40 per cent of the stand and the four-inch from 4.3 per cent to 22.6 per cent. In the heavily thinned plot 50 per cent of the stand was in the two-inch class in 1925. In 1934 this class had dropped to 13.9 per cent while the four-inch class had increased from 22.8 per cent to 36.5 per cent and the five-inch from 5.5 per cent to 28.3 per cent. In the moderately thinned plot the three-inch trees composed 44.5 per cent of the stand in 1925 and 29.3 per cent in 1934; the four-inch trees remained practically stationary; the five-inch trees increased from 4.9 per cent to 21.2 per cent. There has been a more rapid moving up of diameter classes in the thinned stands than in the unthinned. Naturally the loss in numbers in the unthinned check affects the proportion between the diameter classes.

Table 6 gives the analysis of the trees by crown classes on the basis of the 1925 crown classification. One point must be stressed in considering this analysis, that is, the difficulty of arriving at a proper classification of crowns in jack pine stands as dense and as uniform in character as these stands. The clearly suppressed and the clearly dominant are easily recognized, but the border line between intermediate and dominants is rather close and often difficult to recognize.

A study of the distribution of the crown classes as of 1925, the date of the establishment of the thinning, gives probably the best indication of the character of thinning. It shows that in Plot 2 the thinning was largely confined to the suppressed and intermediate trees, while in Plot 1 it extended well up into the dominants. Plot 1, in fact, has the character of a combined low and crown thinning.

Here, as in the analysis of diameter classes, the various crown classes of the heavily thinned show the largest response in diameter growth. An accurate comparison between the crown classes is difficult because of the varying numbers of each class in the three plots. A comparison between the intermediate crown classes of the heavily thinned and moderately thinned plots is possible since the number per acre is nearly the same in each of the plots and the original diameter is nearly the same. At the end of the first five-year period, the intermediates of the heavily thinned plot had increased 0.7 inch in diameter, while in the moderately thinned plot they had increased only 0.4 inch. At the end of the second five-year period, the intermediate tree had in-

Table 6. Analysis of Growth by Crown Classes Based on the 1925 Classification

Crown class	No. of trees per acre		Diameter, inches			Height, feet.			Volume, cubic feet per acre						Periodic increment per acre, cubic feet				Growth, per cent	
	No.	Per cent total	1925	1930	1934	1925	1930	1934	1925	Per cent volume	1930	Per cent volume	1934	Per cent volume	1930	Per cent increment	1934	Per cent increment	1930	1934
CHECK																				
Suppressed	264	13.6	1.9	2.1	2.2	22.0	23.9	24.1	86.20	7.4	102.25	6.3	107.16	5.5	16.08	3.4	4.98	1.6	18.8	4.7
Intermediate	1,192	61.5	2.5	2.8	3.0	24.9	27.7	29.1	642.60	55.6	883.36	54.4	1,028.88	53.4	240.76	51.0	145.52	48.2	37.4	16.4
Codominant	300	15.5	2.8	3.4	3.7	27.1	31.0	33.1	211.92	18.5	318.92	19.6	394.92	20.5	107.00	22.6	76.00	25.2	50.7	23.8
Dominant	184	9.4	3.5	4.2	4.6	29.9	33.9	35.3	212.08	18.5	320.88	19.7	396.60	20.6	108.80	23.0	75.82	25.0	51.0	23.4
Total	1,940	100.0							1,152.80	100.0	1,625.44	100.0	1,927.56	100.0	472.64	100.0	302.32	100.0		
PLOT I, HEAVILY THINNED																				
Suppressed	2	.2	1.9	2.5	2.6	22.0	25.0	25.0	0.50	...	0.62	...	1.04	...	0.12	...	0.42	...	...	...
Intermediate	640	87.0	3.1	3.8	4.3	28.1	29.9	32.1	552.58	76.0	858.52	74.8	1,142.64	75.5	305.04	74.0	290.12	76.8	55.0	33.8
Codominant	66	9.0	4.2	5.2	5.8	32.2	34.4	36.7	104.62	14.3	174.54	15.4	230.42	15.3	69.92	16.8	56.08	14.8	67.0	32.0
Dominant	28	3.8	5.1	6.2	6.9	32.0	37.0	38.0	70.66	9.7	108.56	9.8	139.20	9.2	37.90	9.2	31.64	8.2	52.7	29.8
Total	736	100.0							728.36	100.0	1,142.24	100.0	1,513.30	100.0	413.88	100.0	378.26			
PLOT II, MODERATELY THINNED																				
Suppressed	10	1.0	2.5	2.5	2.5	27.0	27.0	27.0	5.52	0.5	5.62	0.4	5.62	0.3	0.10	...	...	...	...	...
Intermediate	655	64.0	2.9	3.3	3.5	28.6	29.7	30.7	496.17	47.9	634.42	45.3	768.32	43.9	138.25	38.1	133.90	38.5	27.9	21.2
Codominant	202	19.8	3.8	4.3	4.8	30.0	33.1	35.1	262.67	25.3	363.42	25.9	462.87	26.5	100.75	27.8	99.45	28.6	38.0	27.4
Dominant	157	15.2	4.3	5.0	5.6	31.5	35.7	37.8	273.95	26.3	397.07	28.4	511.47	29.3	123.12	34.1	114.40	32.8	45.0	28.7
Total	1,024	100.0							1,038.31	100.0	1,400.53	100.0	1,748.28	100.0	362.22	100.0	347.75			

creased an additional 0.5 inch in the heavily thinned and only 0.2 inch in the moderately thinned plot. The volume increase of this class on the heavily thinned plot was more than double that of the moderately thinned.

It appears from this analysis that the heavy thinning did have more of a stimulating effect upon the lower crown classes and diameter classes than did the moderate thinning. This indicates that a crown thinning would probably give good results when judiciously applied to young stands of jack pine.

The increment as shown by Table 3 for the plots is considerably smaller during the second five-year period than the first. This being a relatively poor site, the hypothesis might be advanced that the effect of the thinning had already disappeared with the rapid consumption of the increased plant food made available immediately after thinning. This would be in accordance with the findings of Hartig (1891). However, the drop is even more marked in the unthinned stand. As has been previously cited, growth in both diameter and height has been more or less successfully correlated with precipitation and temperature. To determine whether or not there had been a difference in growing conditions, the weather records of the past ten years were analyzed. The station where these observations were taken is located one-half mile from the plots in a rather open area at the station headquarters.

Table 7 gives the annual mean temperature and the annual precipitation for the period of 1925 to 1934. The annual means show that the second period was somewhat warmer and drier than the first. The normal mean annual temperature for this station is 38° F. During the first period only one year (1925) showed any appreciable excess and that was only 1.5° F. During the second period the mean annual temperature was above the normal, varying from 0.7° to 6° F. The first period had three years during which the precipitation was above the normal of 26.6 inches, while during three years of the second it was below normal. The conditions during the growing season are possibly a better basis for comparison. These are given in Table 8. These figures show that the second period was considerably warmer and drier than the first. During the first period only one year was much below the normal of 16.97 inches for the growing season and that was 1929, the last year of the period. The effect of this lack of moisture would doubtless be felt during the first year of the second period. During the second period three of the years were below the normal in precipitation. While the distribution of the rainfall during the growing season is also of importance, these figures indicate that in all probability the falling off in rate of growth was due to the warmer and drier conditions prevailing during the second period. There was a total difference of 8.98 inches in precipitation between the two periods, a sufficient amount to affect seriously the growth in a region such as this where precipitation is very nearly a limiting factor.

Table 7. Weather Conditions at the Cloquet Forest 1925-1934

Year	Mean temperature, °F.	Precipitation, inches
1925	39.5	23.16
1926	37.3	31.13
1927	38.4	28.30
1928	38.5	31.72
1929	37.6	23.34
1930	40.2	28.26
1931	44.0	29.33
1932	38.7	25.67
1933	38.9	24.41
1934	39.5	22.41

Table 8. Weather Conditions During Growing Seasons (May-Sept.) 1925-1934

Year	Mean temperature, °F.	Precipitation, inches
1925	59.7	15.96
1926	58.6	19.30
1927	56.8	17.68
1928	58.0	21.96
1929	58.7	14.40
1930	61.1	21.75
1931	61.4	19.15
1932	60.9	14.21
1933	62.3	14.08
1934	60.1	11.23

GROWTH ANALYSIS OF INDIVIDUAL TREES

The results given in Tables 3 to 6 give a complete volume analysis for the plots since the time of thinning. These results were arrived at through the use of volume tables. To further substantiate these results and to give more detailed information as to the progress of growth, both before and after thinning, three typical trees of each of the upper three crown classes were cut and the growth analyzed by five-year periods.

Volumes were computed for each five-year period using Smallian's Formula:

$$V - 4' \times \left\{ \frac{B \text{ stump} + b \text{ tip}}{2} + b_1 + b_2 + b_3 \right\}$$

B = Basal area of the stump

b = Basal area of other sections

The volume of the tip was computed by the formula:

$$V = \frac{b}{2} \times L$$

The volume of the stump by the formula:

$$V = B \times H$$

All volumes in this instance were computed inside bark. The volumes for the plots as given in Tables 3 to 6 include bark.

The results of the stem analysis are given in Table 9. The dominant crown class does not show any great response to thinning. It is true that the average growth for the heavily thinned plot is almost twice that of the unthinned and one-fourth to one-third more than the moderately thinned. On the basis of the ten-year period after thinning, it would seem that there had been a considerable acceleration were it not for the fact that this same ratio existed between the plots in the five years preceding thinning. Dominant trees, as defined by the Society of American Foresters' Committee on Terminology (1917), are "trees with crowns extending above the level of the forest canopy and receiving full light from above and partly from the side, larger than the average trees in the stand, and with crowns well developed but possibly somewhat crowded on the sides." From the definition it can be readily understood that it is possible for a dominant tree to make almost complete use of all the factors of site and that its response to increased opportunity for growth might not be as marked as some of the lower crown classes.

The effect of the thinnings becomes apparent in the codominant crown class. During the five-year period preceding thinning, 1919 to 1924, the average increase of the analyzed codominants in the heavily thinned plot was 0.305 cubic foot in volume; during 1930 to 1934, the second five-year period after thinning, the increase was 0.636 cubic foot. The periodic growth was 0.216 cubic foot larger during the first five-year period and 0.331 cubic foot larger in the second. In the moderately thinned plot the average was 0.268 cubic foot for the five-year period preceding thinning; 0.362 cubic foot for the first five-year period after thinning; and 0.444 cubic foot for the second five-year period. The periodic growth was 0.094 cubic foot larger for the first five-year period following thinning than it was during the five years preceding thinning and 0.176 cubic foot larger for the second five-year period. The average codominant of the unthinned plot increased in volume 0.178 cubic foot from 1919 to 1924, 0.247 cubic foot from 1925 to 1929, and 0.235 cubic foot from 1930 to 1934. The periodic growth was 0.069 cubic foot larger in the first five-year period following the thinning in the other plots and 0.057 cubic foot in the second period. The continued acceleration in growth rate of the trees on the thinned plots is evidence of the stimulating effect of the thinning.

The intermediate crown class shows a somewhat similar effect. In this class the average tree for the heavily thinned plot was growing somewhat slower than those in the moderately thinned and unthinned plots before the thinning took place. During the first five-year period following thinning the rate of growth increased on the heavily thinned plot but decreased still further on the moderately thinned plot and on the unthinned.

In 1924 the average tree of the heavily thinned plot, after thinning, was 3.3 inches in diameter at breast height. It so happened that the three average codominant trees analyzed for the heavily thinned plot were average trees in 1924. The three codominants analyzed from the moderately thinned plot were 3.3, 3.4, and 3.4 inches in diameter in 1924, which would make them comparable to the three trees analyzed from the heavily thinned plot. For purposes of comparison, three trees that were 3.3 inches in diameter in 1924 were selected from the unthinned plot and analyzed. These trees in the unthinned plot were both dominant and codominant trees and were not selected because they were average trees, but because they had a specific diameter in 1924. The codominant trees of the unthinned already discussed were selected because they were average trees for that crown class. By selecting trees having the same diameter at the time of thinning and analyzing the growth, a good indication of the effect of the thinning should be secured. Since they were equal in 1924, any differences in the rate of growth should be the result of the thinning.

During the five years preceding thinning, the growth was practically equal in all three groups, being 0.305 cubic foot in the plot heavily thinned, 0.268 cubic foot in the plot lightly thinned, and 0.281 cubic foot in the plot unthinned. During the first five-year period after thinning, the growth was 0.521 cubic foot in the heavily thinned plot, 0.362 cubic foot in the moderately thinned, and 0.359 cubic foot in the unthinned. During the second five-year period after thinning, the growth was 0.636 cubic foot on the heavily thinned plot, 0.444 cubic foot on the moderately thinned plot, and 0.356 cubic foot on the unthinned plot.

The difference in the rate of growth of these three trees, which were equal in size at the time of thinning, shows that there has been a considerable increase in the rate of growth due to thinning. Since the thinning is the only variable, to which the three groups have been subjected, save that of inherent qualities in the individual, it is reasonable to suppose that this increase is the result of the better growing conditions created because of the thinning.

The dry weight of the needles gives an indication of the difference in crown development. In every instance the greatest crown development was found in the heavily thinned plot, the moderately thinned plot came second, and the unthinned third. In the intermediate crown class occurs an exception. The trees of the moderately thinned plot show a smaller crown development than the trees of the unthinned. This is due in part to the fact that the trees were slightly smaller and to the fact that the crown data on the largest tree of this group were missing. In the case of the three groups of trees that were comparable in 1924, the crown development, as shown by the dry weight of the needles, was approximately three times as great in the heavily thinned stand as in the unthinned stand and twice as great in the moderately thinned stand as in the unthinned stand. In almost every instance the

Table 9. Volume Analysis of Individual Trees of Different Crown Classes for the Three Plots

Tree No.	D.B.H., inches, 1934	Age at stump	Total height, feet	Crown		Weight of needles, oven-dry, grams, 1934	Volume, cubic feet				Growth 1919 to 1924		Growth 1925 to 1929		Growth 1930 to 1934		D.B.H., inches			Nitrogen in needles, per cent dry weight
				Width, feet	Length, feet		1919	1924	1930	1934	cubic feet	per cent periodic	cubic feet	per cent periodic	cubic feet	per cent periodic	1924	1930	1934	
									DOMINANTS—PLOT I, HEAVILY THINNED											
111	7.1	38	43.5	8.9	24.5	5,706	1.724	2.671	3.971	5.178	.947	55.0	1.300	48.5	1.207	30.2	5.4	6.4	7.1	1.40
205	6.8	37	36.5	8.0	21.0	6,493	1.261	1.910	2.789	4.074	.649	51.5	.779	40.6	1.285	46.0	5.1	6.1	6.8	1.25
332	7.5	36	41.0	9.1	29.5	9,338	1.619	2.599	4.247	6.020	.980	60.5	1.648	63.5	1.773	41.7	5.5	6.7	7.5	1.23
Total		111	121.0	26.0	75.0	21,537	4.604	7.180	11.007	15.272	2.576	......	3.727	......	4.265	......	......	......	......	3.88
Average		37	40.3	8.6	25.0	7,179	1.535	2.393	3.669	5.090	.858	55.7	1.242	52.0	1.422	38.8	......	......	......	1.29
									PLOT II, MODERATELY THINNED											
32	6.1	37	44.5	7.8	24.0	5,989	1.225	1.870	2.846	4.187	.645	52.7	.976	52.0	1.341	47.0	4.7	5.4	6.1	1.25
103	5.7	37	40.5	6.0	19.0	3,117	1.109	1.664	2.426	3.271	.555	50.0	.762	45.7	.845	34.8	4.8	5.2	5.7	1.27
191	6.2	37	41.5	5.2	17.0	3,762	1.178	1.907	2.912	4.115	.729	61.7	1.005	52.7	1.203	41.2	4.7	5.6	6.2	1.17
Total		111	126.5	19.0	60.0	12,868	3.512	5.441	8.184	11.573	1.929	......	2.743	......	3.389	......	......	......	......	3.69
Average		37	42.2	6.3	20.0	4,289	1.170	1.817	2.728	3.858	.643	55.0	.914	50.2	1.129	41.2	......	......	......	1.23
									UNTHINNED											
56	4.8	37	33.0	4.7	12.2	1,940	.664	1.032	1.389	1.876	.368	55.5	.357	34.6	.487	35.0	4.0	4.4	4.8	1.16
622	5.3	36	36.5	7.2	18.0	2,660	.551	.934	1.532	2.182	.383	69.5	.598	64.0	.650	29.8	4.0	4.9	5.3	1.24
641	5.5	37	39.5	5.6	18.0	3,213	1.016	1.585	2.406	3.258	.569	56.0	.811	51.2	.852	35.4	4.4	5.1	5.5	1.14
Total		110	109.0	17.5	48.2	7,813	2.221	3.551	5.327	7.316	1.320	......	1.776	......	1.989	......	......	......	......	3.54
Average		36.6	36.3	5.8	16.1	2,604	.740	1.184	1.776	2.437	.440	59.5	.592	50.0	.663	37.4	......	......	......	1.18
									CODOMINANTS—PLOT I, HEAVILY THINNED											
38	4.9	36	31.5	6.2	11.2	2,436	.545	.876	1.483	2.138	.331	60.7	.607	69.5	.655	44.2	3.3	4.3	4.9	1.16
105	5.5	36	32.5	4.5	15.0	4,843	.574	.810	1.355	1.908	.236	41.1	.545	67.5	.553	40.0	3.3	4.2	5.5	1.24
173	4.6	35	36.5	5.2	17.0	2,462	.442	.791	1.203	1.902	.349	79.0	.412	52.0	.699	58.0	3.3	4.0	4.6	1.34
Total		107	100.5	15.9	43.0	9,741	1.561	2.477	4.041	5.948	.916	......	1.564	......	1.907	......	......	......	......	3.74
Average		35.6	33.5	5.3	14.3	3,247	.520	.826	1.347	1.983	.305	58.7	.521	63.0	.636	47.2	......	......	......	1.25
									PLOT II, MODERATELY THINNED											
29	4.5	35	32.5	5.6	21.0	2,322	.381	.707	1.086	1.799	.326	85.5	.379	53.7	.713	65.5	3.4	4.0	4.5	1.28
66	4.1	37	37.5	3.5	15.5	2,500	.539	.781	1.174	1.632	.242	45.0	.393	51.0	.448	38.2	3.3	3.8	4.1	1.30
114	4.0	37	31.5	4.6	13.3	1,550	.586	.822	1.137	1.308	.236	41.0	.315	38.3	.171	15.0	3.4	4.0	4.0	1.35
Total		109	101.5	13.7	49.8	6,372	1.506	2.310	3.397	4.739	.804	......	1.087	......	1.332	......	......	......	......	3.93
Average		36.3	33.8	4.6	16.6	2,124	.502	.770	1.132	1.579	.268	53.0	.362	47.0	.444	39.2	......	......	......	1.31

Table 9—Continued

Tree No.	D.B.H., inches, 1934	Age at stump	Total height, feet	Crown: Width, feet	Crown: Length, feet	Weight of needles, oven-dry, grams, 1934	Volume, cubic feet: 1919	Volume, cubic feet: 1924	Volume, cubic feet: 1930	Volume, cubic feet: 1934	Growth 1919 to 1924: cubic feet	Growth 1919 to 1924: per cent periodic	Growth 1925 to 1929: cubic feet	Growth 1925 to 1929: per cent periodic	Growth 1930 to 1934: cubic feet	Growth 1930 to 1934: per cent periodic	D.B.H., inches: 1924	D.B.H., inches: 1930	D.B.H., inches: 1934	Nitrogen in needles, per cent dry weight
									UNTHINNED											
161	3.2	35	29.5	3.5	9.0	....	.204	.370	.624	.851	.166	81.5	.254	68.7	.227	36.4	2.4	2.9	3.2	....
594	3.4	37	36.5	3.0	12.0	820	.310	.516	.804	1.070	.206	67.2	.288	55.9	.266	33.1	2.7	3.1	3.4	1.29
699	3.4	36	31.5	6.0	11.0	801	.394	.556	.756	.967	.162	41.2	.200	35.9	.211	27.9	3.0	3.2	3.4	1.35
Total		108	97.5	12.5	32.0	1,621	.908	1.442	2.184	2.888	.534	....	.742	....	.704	....	......	......	......	2.64
Average		36	32.5	4.2	10.6	810	.303	.481	.728	.963	.178	58.7	.247	51.3	.235	32.3	......	......	......	1.32
									INTERMEDIATES—PLOT I, HEAVILY THINNED											
117	2.8	32	24.5	2.6	11.2	684	.167	.239	.364	.484	.072	43.0	.125	52.2	.120	45.5	2.2	2.5	2.8	1.20
181	3.3	33	28.5	3.5	15.3	1,274	.156	.247	.464	.800	.091	54.1	.217	88.0	.356	42.0	2.0	2.7	3.3	1.39
342	2.6	34	24.5	4.0	12.5	626	.182	.243	.344	.421	.061	33.5	.101	41.5	.077	22.4	2.0	2.4	2.6	1.30
Total		99	77.5	10.1	39.0	2,584	.505	.729	1.172	1.705	.224	....	.443	....	.553	....	......	......	......	3.89
Average		33	25.8	3.4	13.0	861	.168	.243	.390	.568	.075	44.6	.148	61.0	.178	45.6	......	......	......	1.29
									PLOT II, MODERATELY THINNED											
9	3.7	35	28.5	3.9	10.7	....	.517	.729	.873	.984	.212	41.0	.144	19.8	.111	12.2	3.4	3.5	3.7	....
21	2.2	32	29.5	2.2	8.7	163	.081	.177	.235	.330	.096	118.0	.058	32.7	.095	40.3	1.9	2.1	2.2	1.43
98	2.2	31	30.5	5.2	8.8	165	.120	.229	.334	.389	.109	91.0	.105	45.7	.055	14.1	2.1	2.2	2.2	1.36
Total		98	88.5	11.3	28.2	328	.718	1.133	1.442	1.703	.417	....	.307	....	.261	....	......	......	......	2.79
Average		32.6	29.5	3.8	9.4	164	.239	.378	.481	.568	.139	58.2	.102	27.0	.087	18.1	......	......	......	1.39
									UNTHINNED											
14	2.4	31	28.5	3.0	12.0	303	.184	.312	.383	.438	.128	69.5	.071	22.7	.045	11.7	2.4	2.4	2.4	1.37
71	2.5	35	28.5	2.2	7.0	319	.284	.385	.476	.537	.101	35.7	.091	23.6	.061	11.4	2.4	2.5	2.5	1.41
140	3.0	35	29.5	3.2	16.6	896	.121	.220	.437	.672	.099	81.5	.217	98.5	.235	53.7	2.1	2.6	3.0	1.32
Total		101	86.5	9.4	35.6	1,518	.589	.917	1.296	1.647	.328	....	.379	....	.341	....	......	......	......	4.10
Average		33.6	28.8	3.1	11.8	506	.196	.306	.432	.549	.109	55.6	.126	41.2	.113	26.2	......	......	......	1.36
									UNTHINNED, 3.3 INCHES D.B.H.											
546	4.5	35	35.5	4.5	19.5	1,475	.353	.688	1.101	1.584	.335	85.3	.413	60.0	.483	43.7	3.3	4.0	4.5	1.41
683	4.0	33	32.7	5.0	17.2	1,165	.461	.722	1.053	1.329	.261	56.7	.331	45.7	.276	26.2	3.3	3.8	4.0	1.35
692	3.9	37	35.5	3.2	13.5	848	.542	.789	1.122	1.432	.247	45.6	.333	42.2	.310	25.4	3.3	3.7	3.9	1.35
Total		105	103.7	12.7	50.2	3,488	1.356	2.199	3.276	4.345	.843	....	1.077	....	1.069	....	......	......	......	4.11
Average		35	34.6	4.2	16.7	1,163	.452	.733	1.092	1.448	.281	62.2	.359	49.0	.356	32.6	......	......	......	1.37

crowns were wider and longer in the heavily thinned plot than in the unthinned and moderately thinned plots.

From the sample trees analyzed for each crown class, the individual tree with a diameter corresponding most nearly to the average for that crown class, as shown in Table 6, was selected as a mean sample tree for that crown class. While this would be questionable practice in volume computations, a slight variation in diameter should not seriously affect the computation of the crown development. Using this tree as the average, the total weight of needles per acre for each crown class was computed and from this the total for each plot. It is admitted that the results are only roughly approximate, since a great many more crowns would be needed to secure a statistically accurate average. However, the results are sufficiently accurate to indicate the difference in the crown development of the three plots. The results are shown in Table 10. The heavily thinned plot with the fewest trees per acre had the greatest quantity of needles and consequently the greatest leaf surface. The moderately thinned stand was second, with 100 kilograms less per acre, while the unthinned plot with almost three times the number of trees found on the thinned plot and twice the number found on the moderately thinned plot had approximately 200 kilograms less needles per acre than the heavily thinned plot and 100 kilograms less per acre than the moderately thinned plot.

Table 10. Crown Development on the Three Plots As Indicated by Oven-Dry Weight of Needles

Crown class	Number of trees per acre	D.B.H. Ave. tree	D.B.H. Sample tree	Weight of needles, sample tree, gms.	Number needles, sample tree	Weight of needles per acre, kgs.	Number of needles per acre
			UNTHINNED				
Dominant	184	4.6	4.8	1,940	329,800	360.84	60,683,200
Codominant	300	3.7	4.0	1,165	204,600	349.50	61,380,000
Intermediate	1,176	3.1	3.0	896	160,384	1,053.96	188,611,584
Suppressed	264	2.1	2.1	460	50,140	121.44	10,356,960
Total	1,924	......	......	....	....	1,885.74	321,031,744
			HEAVILY THINNED				
Dominant	28	6.9	6.8	6,493	757,095	181.40	21,198,660
Codominant	66	5.8	5.5	4,843	625,958	319.64	41,313,228
Intermediate	640	4.4	4.6	2,462	244,969	1,575.68	156,780,160
Suppressed	....	......	......	....	....	....	....
Total	734	......	......	....	....	2,076.72	219,292,048
			MODERATELY THINNED				
Dominant	159	5.5	5.7	3,117	390,404	494.60	62,084,236
Codominant	202	4.8	4.5	2,322	267,030	469.04	53,940,060
Intermediate	655	3.5	4.0	1,550	204,600	1,015.25	134,013,000
Suppressed	10	2.5	2.2	165	29,177	.16	291,770
Total	1,026	......	......	....	....	1,979.05	250,329,066

Counts of samples of the needles were made from all the trees to determine the number of needles per kilogram. These figures were used in determining the leaf area per acre using the formula suggested by Korstian (1921) and the measurements for the needles in Table 37. No attempt was made to compute the leaf area for individual trees, since the measurements of the needles were a composite of all trees on the plot. Table 11 gives the area of leaf surface in square meters per acre for each of the three plots.

Table 11. Leaf Area Per Acre for the Three Plots, 1934, Ten Years After Thinning

Plot	Area, square meters per acre	Per cent excess over the unthinned
Unthinned	1,040,725	....
Heavily thinned	1,392,705	33.8
Moderately thinned	1,230,619	18.2

The heavily thinned plot had a leaf area 33.8 per cent greater than the unthinned, while the leaf area of the moderately thinned plot exceeded the unthinned plot by 18.2 per cent. This rather significant difference may be an abnormal situation which does not give the true picture of the leaf areas of the three plots during the entire period following thinning.

Under the indirect effects of precipitation is discussed the effect of a sleet storm occurring early in April 1934. This removed 0.5 per cent of the leaf area in the unthinned plot, 0.2 per cent of the leaf area of the heavily thinned plot, and 0.3 per cent of the leaf area of the moderately thinned plot. These percentages are based on the fall foliage, which does not include the new season's needles that were not present at the time of the storm. Since the loss was not only in needles but also in buds, the damage resulting must include consideration of the loss in ability to produce new needles. This was naturally much greater in the unthinned plot than in the two thinned areas. Had the loss of growing tips not occurred, it is probable that the leaf area of the unthinned plot might have been as large or larger than that of either of the thinned plots.

The quantity of needles is not always in proportion to the growth rate. Tree No. 105 of the codominant crown class from the heavily thinned plot had twice the quantity of needles that the other two trees (Nos. 38 and 173) possessed. Yet during the last five-year period this tree increased in volume 0.553 cu. ft., while tree No. 38 increased 0.655 cu. ft., and tree No. 173 increased 0.699 cu. ft. Tree No. 38 had a wider but shorter crown than tree No. 105, while tree No. 173 had a wider and longer crown. Both trees No. 105 and No. 173 were growing with free crowns while tree No. 38 was slightly crowded by two neighboring trees. Evidently such things as the distribution of the needles and the unknown inherited characteristics enter into the question of rate of growth. Possibly a better test would be a comparison of the dominant trees, since in this crown class all of the foliage is placed in the most advantageous position. In this crown class the greatest volume increase is associated with the greatest crown volume.

FACTORS OF HABITAT AS AFFECTED BY THINNING

Method of Study

During the growing seasons of 1933 and 1934, observations were taken of the various factors of habitat on each of the three plots. The purpose was to determine to what extent these factors had been altered by the thinning operation. A wooden tower was erected in the center of each plot to permit the placing of the instruments at the midpoint of the live crown. A similar set of instruments was installed at the base of each tower to determine conditions at the ground level. Air temperatures were recorded by means of standard maximum and minimum thermometers placed in standard shelters facing north. The thermometers were read at 5 o'clock. Evaporation was measured by means of Livingston spherical porous cup atmometers, using a black and white bulb at each station in the crowns and at the surface. Humidity readings were taken both in the crowns and at the ground level at 8 a.m., 1 p.m., and 5 p.m. with a standard sling psychrometer. Rainfall was measured with a standard 8-inch rain gauge. Surface soil temperatures were read at 8 a.m., 1 p.m., and 5 p.m. from a standard thermometer with the bulb placed in the surface soil. Readings of soil temperatures at 6-, 12-, and 24-inch depths were taken at 5 o'clock from standard soil thermometers. Soil moisture samples were taken at random in each of the three plots three times each week. These samples included the duff and litter, 1-inch, 6-inch, 12-inch, and 24-inch depths. The samples were sealed in airtight cans, weighed at once, and dried to constant weight in an electric oven at a temperature of 130° F. for a period of 48 hours.

It is recognized that more accurate results might have been secured by the use of recording instruments. Adams (1930) and Burns (1918) maintain that extremes of relatively short duration, not apparent in daily readings, often have a marked effect upon the growth. Lundegardh (1925) states that the rate of growth changes with small changes in temperature which may or may not be important. Dengler (1930) maintains that extremes of temperature are not important as far as native species are concerned. Instances of the occurrence of extremes which seriously affect the growth of indigenous species are relatively rare. Such extremes are not a factor as far as this study is concerned, since the effect would probably be felt on all three plots studied. Early in April 1934, before observations began, a heavy rain storm occurred that froze on the trees. Heavy winds following broke off a large number of the tips of branches. The loss of such a considerable leaf area probably affected the current season's growth. The loss was much greater in the unthinned stand than in the thinned stand. Detailed data on this occurrence will be presented later.

The relationship between the three plots can be shown with a sufficient degree of accuracy by means of daily readings from non-recording instruments. Since this is essentially a study of the microclimate of the forest within a uniform site, it is reasonable to suppose that the various factors will be correlated and will be somewhat similar. Changes in the general weather conditions would produce somewhat similar changes on all three plots. Two methods of presenting the data will be followed. The first will be a chronological comparison in some instances of daily records, in other instances of ten-day or monthly averages, as suggested by Bates and Zon (1922), to show seasonal trends.

The second method will be the one suggested by Harris, Kuenzel, and Cooper (1929), whereby it is possible to correlate the data statistically and to check accurately the significance of any differences. In this method the paired daily readings are plotted in a two-dimensional plane. Empirical means are computed to serve as a rough check and to show the general location and trend of the fitted line. The correlation coefficient, r, is computed by the standard formula.

$$r = \frac{\Sigma AX - (\Sigma A)\ Mx}{\sqrt{\Sigma A^2 - (A)\ M_A}\ \sqrt{\Sigma X^2 - (\Sigma X)\ M_X}}$$

where $A\ X$ = sum of the products
A = sum of the observations A
MA = mean of the variable A

The regression equation which gives the trend of the fitted line is figured by the formula:

$$\overline{X} = M_X + r \frac{\sqrt{\Sigma X^2 - (\Sigma X)\ M_X}}{\sqrt{\Sigma A^2 - (\Sigma A)\ M_A}} (A - M_A)$$

These formulas are in accordance with those suggested by Wallace and Snedecor (1931).

To test the significance of the differences between the means of the site factors, Harris (1929) used the formula for the probable error of the differences for correlated variables. In the present study, however, the standard error of the differences was used. The formula for this is:

$$\Sigma_{(\overline{A} - \overline{X})} = \frac{\sqrt{\sigma A^2 - \sigma X^2 - 2r_{AX}\,\sigma A\,\sigma X}}{\sqrt{N}}$$

$\overline{A}$ = mean of A
$\overline{X}$ = mean of X
σA = standard deviation of A
σX = standard deviation of X
r = correlation of coefficient
N = number of observations
A ratio of 2 and 2.6 set up as a level of significance.

Air Temperature

Air temperature is a factor of fundamental importance, altho its effect is not directly visible in the tree. Lundegardh (1925) states that it is the master factor of distribution, but that it never operates alone. Hansen and Brenke (1926) found that cell division in *Fraxinus campestris* and *Acer saccharinum* was more active at mean temperatures below 60° F. than at higher temperatures. Lundegardh (1925) states that optimal conditions for the accumulation of carbohydrates in sun plants require a day temperature of from 10 to 30° C. The significance of night temperatures decreases towards the poles. Amilon (1910) found that a temperature of 70° F. was necessary for cell division in Scotch pine in Sweden. He maintains that early spring insolation is more important than air temperatures for the start of growth. Laitakari (1920) maintains that early spring temperatures control the diameter growth, while height growth is dependent upon temperature of the previous summer. Eide (1926) was able to correlate diameter growth with the current season's temperature. He found, in Norway, that the temperature from June 10 to 25 was the most important in its influence upon growth rate. When it was higher than 13.7° C. growth increased, when lower growth decreased. Lehenbauer (1914), working with corn, found an increase in the rate of growth up to a maximum temperature after which the rate of increase fell off with further increase in temperature. Livingston's (1916) physiological indices based on Lehenbauer's work to show the effect of temperature on growth are probably not yet entirely reliable. Adams (1929) states that they were not applicable when applied to jack pine. This is probably due to the fact that, as Lundegardh (1925) states, temperature seldom operates alone. Often changes in one factor may be accompanied by compensating or aggravating changes in other factors. Physiologists in general agree that physiological activities increase up to about 25° C. (77° F.) Above this point the initial rate of increase is not maintained, and the higher the temperature the faster the growth rate falls off.

The thinning changed the crown density of the stand very markedly. This should have a direct influence upon the air temperature, since it affected both the wind movement and insolation. Table 12 gives the monthly averages for the maximum, minimum, and mean temperatures in the crowns and at the surface stations in the three plots. These data are not shown in graphic form since the graphic presentation of the chronological data does not show anything that can not be interpreted from the statistical presentation given later. The data for the two seasons agree in the relationship between the three plots. There is less difference in the air temperature of the crown stations at the beginning and end of the growing season than during the middle part of the growing season. Factors which influence the air temperatures in one plot have a similar influence in the other plots, altho to a different degree. The maximum temperatures in the crowns of the unthinned stand are higher than in the thinned stand, while the minimums are lower. Jack pine has a relatively small and open crown allowing considerable sunlight to pass through. The greater density of the unthinned stand prevented free air circulation and thus raised the maximum temperature and lowered the minimum in the crowns. The mean temperatures lie fairly close together.

Table 12. Air Temperatures (°F.), Monthly Mean Averages of the Three Plots

Monthly mean	Surface			Crown		
	Max.	Min.	Mean	Max.	Min.	Mean
			UNTHINNED			
1933						
July	80.3	54.0	67.1	83.3	53.9	68.6
August	76.5	49.6	63.0	79.1	49.5	64.3
September	70.7	48.6	59.6	73.0	48.5	60.7
1934						
May	73.4	38.4	55.9	74.5	40.1	57.3
June	76.4	46.3	61.3	77.6	47.4	62.5
July	80.7	51.8	66.2	83.3	50.7	67.0
August	74.2	48.5	61.3	76.9	47.4	62.1
September	63.7	44.4	54.0	65.4	42.5	53.9
			HEAVILY THINNED			
1933						
July	83.0	54.1	68.5	81.5	53.9	67.7
August	79.2	47.5	63.3	77.5	49.4	63.4
September	73.0	48.5	60.7	72.5	48.7	60.6
1934						
May	74.2	40.0	57.1	73.1	41.3	57.2
June	77.4	48.3	62.8	76.1	48.7	62.4
July	82.8	51.7	67.2	81.3	51.9	66.6
August	76.0	48.3	62.1	75.3	48.4	61.8
September	64.1	44.0	54.0	64.5	43.6	54.0
			MODERATELY THINNED			
1933						
July	81.3	54.0	67.6	81.1	54.4	67.7
August	77.2	48.9	63.0	76.5	49.4	62.9
September	71.5	48.5	60.0	71.6	48.7	60.1
1934						
May	73.9	40.7	57.3	73.3	42.0	57.6
June	76.9	49.8	63.3	76.4	48.3	62.3
July	81.7	52.1	66.4	81.6	52.2	66.9
August	74.9	48.8	61.9	75.5	48.4	61.9
September	64.4	44.4	54.4	64.5	43.6	54.0

The thinning has had more effect upon the air temperature at the surface than in the crowns. Here both the maximum and minimum temperatures are higher in the thinned stands than in the unthinned. The degree of thinning influences the degree of increase in temperature. The heavily thinned stand is the highest, the moderately thinned next, and the unthinned lowest. The increased insolation, which resulted in higher soil temperatures, had more influence upon the air temperature at the ground level than in the crowns. The mean temperatures of the unthinned stand at the surface were of course somewhat lower than the unthinned.

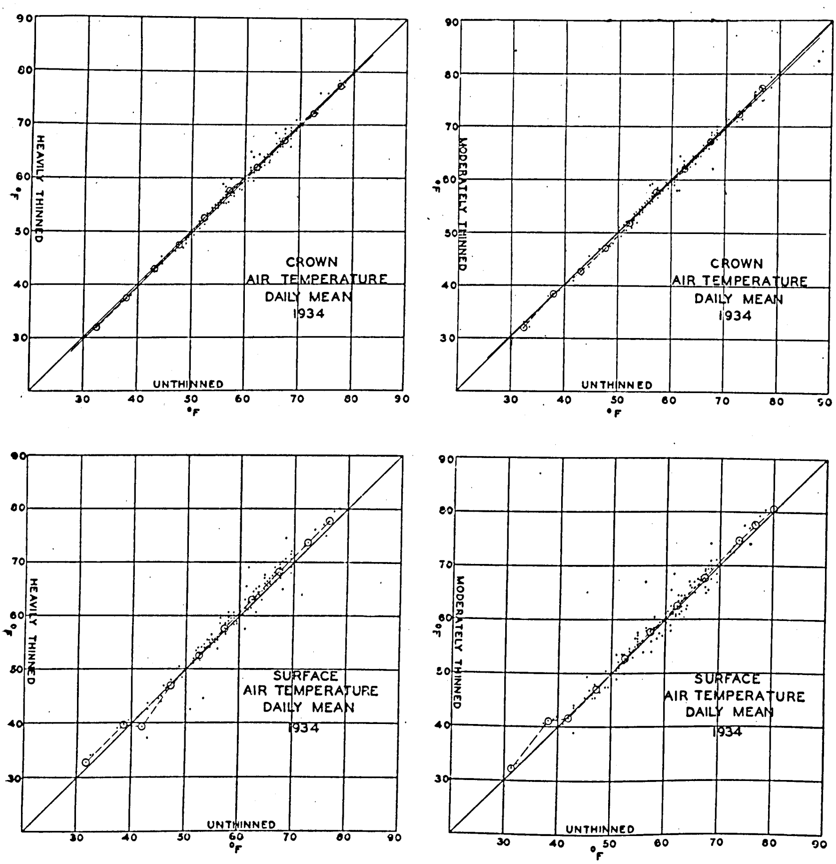

FIG. 4. SCATTER DIAGRAMS SHOWING DAILY MEAN TEMPERATURE IN THE CROWN AND AT THE SURFACE FOR THE THINNED AND UNTHINNED PLOTS

In the unthinned stand, the maximum temperatures were higher in the crowns than at the surface. The minimum temperatures were higher in the crowns until the middle of June, after which they were lower. Wallen (1932) in a similar study made in Sweden secured like results.

In the heavily thinned stand the maximums were higher at the surface than in the crowns, save at the extreme end of the growing season. The minimum temperatures at the surface and in the crown bear the same relationship as in the unthinned stand. In the moderately thinned stand the effect of thinning was to lower the maximum crown temperatures to that of the surface, while the minimum temperatures were slightly lower in the crown early in the season, slightly higher during the middle part, and again lower later in the season.

The statistical comparison of the mean air temperature in the three plots is given in Figure 4. The paired daily readings, the empirical means, and the fitted lines for the mean air temperature at the surface show that they were slightly higher in the thinned than in the unthinned stands. At the crown level, however, the paired readings, empirical means, and the fitted line nearly coincide with the line of equality. This indicates that the thinning had more effect upon air temperatures at the surface than in the crowns. The significance of these differences can be checked statistically. Table 13 gives the correlation coefficient and regression equation for the air temperatures.

Table 13. Correlation Coefficients Between Air Temperatures in the Thinned and Unthinned Stands and the Regression Equation Measuring the Relationship

Air temperature °F.	Correlation-coefficient		Linear regression equation	
	Moderately thinned	Heavily thinned	Moderately thinned	Heavily thinned
Crown	+0.982	+0.991	M T = +0.982 U T +0.81	H T = +0.997 U T −0.01
Surface	+0.952	+0.969	M T = +0.962 U T +2.64	H T = +0.997 U T +0.74

Table 14 gives the differences between the means of the air temperature and the significance of these differences.

Table 14. Differences Between the Means of Air Temperatures in the Thinned and Unthinned Stands and Tests of Significance

Air temperature, ° F.	Moderately thinned			Heavily thinned		
	Difference of means	Standard error of difference	Ratio of difference to its standard error	Difference of means	Standard error of difference	Ratio of difference to its standard error
Crown	−2.5	0.14	1.8	−0.21	0.10	2.1
Surface	+4.0	0.23	1.7	+0.58	0.19	3.1

A ratio of 2 between the difference and its standard error is significant, and 2.6 is highly significant. The results given in Table 14 show that mean air temperature of the crown level in the heavily thinned stand was significantly lower than the unthinned, while at the surface level it was higher and the difference was highly significant. In the moderately thinned stand the ratio fell slightly below the level of significance but took the same direction as in the heavily thinned stand. Even tho the difference between the moderately thinned and unthinned stand is not significant statistically, it may be of importance from a physiological standpoint.

Precipitation

The effect of the thinning operation upon precipitation is rather indirect and mechanical in nature. Naturally it would have no influence upon the occurrence or magnitude of the precipitation. It would have an influence upon the amount of precipitation reaching the ground, which in turn might affect the soil moisture content. It was found that there was considerable variation in the individual storms, even over this limited area. Humphrey (1933) found that there was considerable variation in desert rainfall, even over limited areas. This variation is brought out clearly by Figure 5, which shows the rainfall for the 1934 growing season.

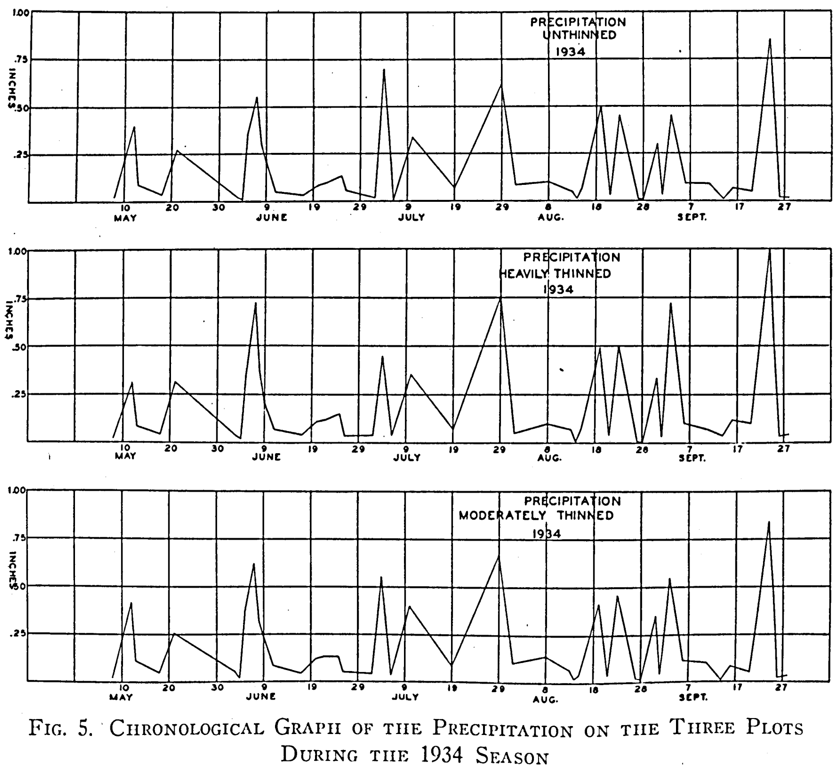

FIG. 5. CHRONOLOGICAL GRAPH OF THE PRECIPITATION ON THE THREE PLOTS DURING THE 1934 SEASON

In the storm which occurred on June 6, 1934, the heavily thinned plot showed the greatest amount reaching the ground, with the moderately thinned plot second, and the unthinned last. In the storm of July 4, 1934, the greatest amount was recorded in the unthinned stand and the least in the heavily thinned stand. Taking the season as a whole, the heavily thinned stand showed the greatest amount, with the moderately thinned second, and the unthinned last.

A better understanding might be secured by comparing the three plots with the gauge at the Cooperative Weather Bureau Station located in the open about a half mile from the plots. As suggested by Beal (1934), the monthly rainfall is taken as a basis of comparison of the three plots with the gauge in the open for the two growing seasons.

Table 15. Relation Between Rainfall Reaching the Ground in the Three Plots and in the Open

Period	Rainfall in open, inches		Rainfall in the Three Plots (per cent of the open)					
			Unthinned		Heavily thinned		Moderately thinned	
	1933	1934	1933	1934	1933	1934	1933	1934
May	......	0.98	......	78	......	78	......	88
June	......	3.07	......	62	......	71	......	71
July	2.72	1.94	79	90	82	86	79	90
August	1.21	2.12	67	76	86	81	76	81
September	3.06	3.12	98	68	102	87	110	73
Season	6.99	11.23	85	73	91	81	91	78

The monthly records show a considerable variation from month to month and between seasons. The seasonal totals, however, show a rather constant relationship between the amount of rainfall reaching the ground and the degree of thinning. The seasonal per cent is in keeping with the results secured by Mitchell (1930) in a study in Wisconsin, where it was found that 80 per cent of the rainfall reached the ground in a jack pine stand. Beal (1934) found that 60 per cent of the season's rainfall reached the ground in a white and red pine forest and 80 per cent in a hardwood. The presence of leaves on the hardwoods seemed to make little difference in the amount reaching the ground. The total amount of rainfall in any month does not show any relationship to the amount reaching the ground. The density of the stand is not the only factor which affects the amount of precipitation reaching the ground. The wind velocity and direction, the character of the storm and its tendency to show local variations are important factors that must be considered.

Table 16 gives the monthly precipitation for the three plots.

Table 16. Monthly Precipitation (Inches) for the Three Plots

Month	Unthinned		Heavily thinned		Moderately thinned	
	1933	1934	1933	1934	1933	1934
May	......	0.77	......	0.76	......	0.86
June	......	1.91	......	2.19	......	2.17
July	2.17	1.75	2.23	1.70	2.15	1.77
August	0.81	1.61	1.05	1.72	0.92	1.73
September	3.00	2.11	3.13	2.73	3.38	2.28
Total	5.98	8.15	6.41	9.10	6.45	8.81
Per cent of unthinned			107.2	111.6	107.9	108.1

Considering the season as a whole, the heavily thinned stand showed the greatest amount of precipitation reaching the ground during both seasons. In 1933 the precipitation reaching the ground in the heavily thinned stand was 7.2 per cent greater than in the unthinned, while in 1934 it was 11.6 per cent greater. In the moderately thinned stand the excess was 7.9 per cent in 1933 and 8.1 per cent in 1934.

Evaporation and Humidity

Evaporation and humidity are closely related factors. Variations in temperature and wind velocity cause changes in each of these factors. Relative humidity varies inversely with the air temperature, while in a general way evaporation varies directly with the air temperature. The humidity and evaporation are indications of the rate of transpiration loss. Transpiration does not follow the course of evaporation exactly because of the action of the stomata. As shown by Stålfelt (1934), the type of weather influences the character of the stomatal openings and consequently the amount of transpiration. Excessive transpiration leads to wilting. In this study we are not concerned with the extremes, since it is hardly conceivable that the thinning operation would cause changes drastic enough to have serious consequences. It is likewise difficult to evaluate the significance of any differences in humidity or evaporation rate.

The monthly averages for relative humidity are given in Table 17. These results show that the relative humidity is lowest in the heavily thinned stand both at the surface and in the crowns. The relative humidity in the moderately thinned and unthinned stands is practically identical.

In comparing the relationship between the surface and the crowns, we find that the relative humidity is higher at the surface than in the crowns in each plot, but that the smallest difference between the two stations occurs in the heavily thinned plot.

Table 17. Relative Humidity for the Three Plots (Monthly Averages Based on Three Daily Readings)

Date (Monthly mean)	Unthinned: Relative humidity, per cent		Heavily thinned: Relative humidity, per cent		Moderately thinned: Relative humidity, per cent	
	Surface	Crown	Surface	Crown	Surface	Crown
1933						
July	64.6	60.6	62.5	60.8	64.8	60.3
August	62.8	58.0	58.4	57.0	60.3	57.9
September	70.2	67.1	67.2	66.8	72.3	68.2
1934						
May	48.3	47.1	47.8	49.2	48.9	48.4
June	62.0	62.9	63.3	62.5	64.5	58.7
July	56.0	54.5	54.1	53.6	55.9	54.6
August	63.0	60.3	61.3	59.4	64.4	60.9
September	78.3	78.4	77.9	77.0	78.7	78.3

Figure 6 gives the statistical comparison between the relative humidity on the thinned and unthinned plots. These charts show that there is very little difference in relative humidity between the thinned and unthinned stands either at the surface or in the crowns.

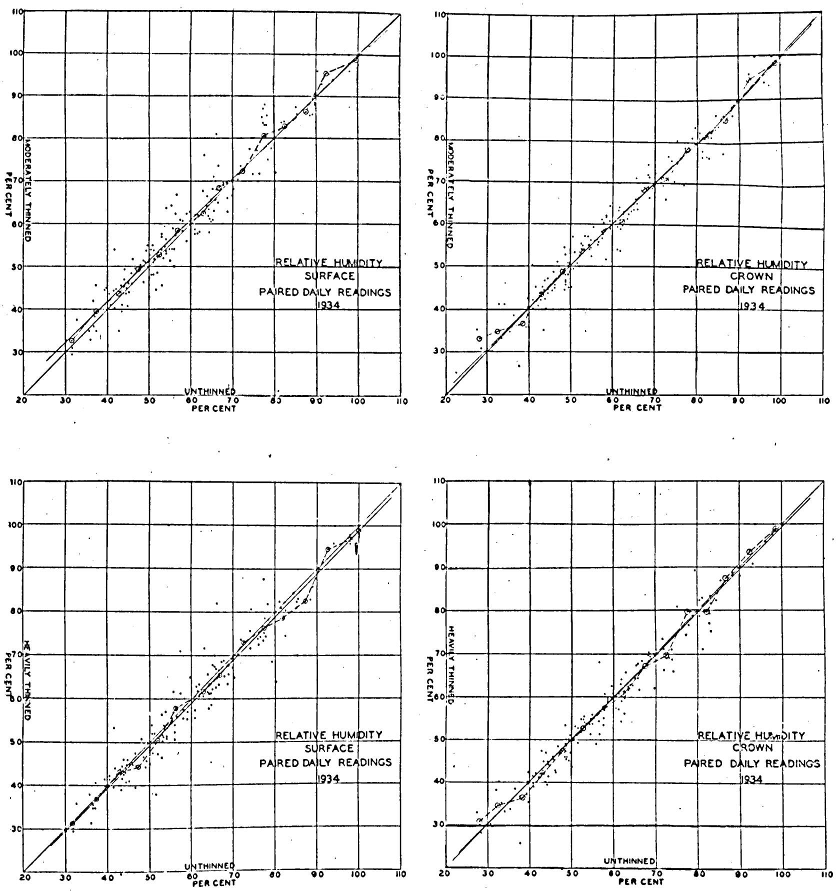

FIG. 6. SCATTER DIAGRAMS SHOWING AVERAGE RELATIVE HUMIDITY AT THE SURFACE AND IN THE CROWNS FOR THE THINNED AND UNTHINNED PLOTS

Table 18 gives the correlation coefficient and regression equation and Table 19 the test of significance of the difference.

Table 18. Correlation Coefficient Between Relative Humidity in Thinned and Unthinned Stands and the Regression Equation Measuring the Relationship

Relative humidity, per cent	Correlation coefficient		Linear regression equation	
	Moderately thinned	Heavily thinned	Moderately thinned	Heavily thinned
Crown	+0.931	+0.931	M T = +0.983 U T +1.31	H T +0.985 U T +0.61
Surface	+0.945	+0.971	M T = +0.959 U T +3.62	H T +0.988 U T +0.12

Table 19. Differences Between the Means of Relative Humidity in Thinned and Unthinned Stands and Tests of Significance

Relative humidity, per cent	Moderately thinned: Difference of means	Standard error of difference	Ratio of difference to its standard error	Heavily thinned: Difference of means	Standard error of difference	Ratio of difference to its standard error
Crown	+3.2	0.18	1.8	−3.1	0.26	1.2
Surface	+1.17	0.44	2.7	−6.2	0.32	1.9

The relative humidity is significantly higher at the surface in the moderately thinned stand than in the unthinned stand. At the crown level it is also higher, but not significantly so. In the heavily thinned stand the humidity is lower both at the crown level and surface, but not significantly so. Just why there should be this difference between the two thinned plots, it is difficult to say. Were it not for the fact that the evaporation data check this difference, it might be supposed to be due to an instrumental error.

In a general way, the evaporation rate follows the relative humidity inversely. The points of high evaporation are usually the points of low relative humidity. Table 20 shows the monthly average and seasonal total from both the black and white spherical atmometers for the two seasons. The heavily thinned plot shows a considerably higher evaporation rate at the surface than the unthinned and moderately thinned plots. In the crowns the difference was not so marked in the 1934 season. The 1933 records, however, are not as reliable as the 1934 due to a less accurate field technique.

At all the stations the rate of evaporation is greater in the crowns than at the surface. The difference in rate between the surface and crowns is greater in the case of the black bulbs than the white, indicating more light in the open crowns of jack pine than on the forest floor. The difference in rate of evaporation between the black bulb at the crown level and at the surface is greatest in the unthinned stand where the least amount of light reaches the surface.

A comparison of the rate of evaporation from the black and white bulbs should indicate the difference in light intensity. In all cases the evaporation is greater in crowns. The difference between the surface and crown stations is greater in the case of the black bulb, indicating more light in the open crowns of jack pine than on the forest floor. This difference is greatest in the unthinned stand.

Figure 7 gives the statistical comparison of evaporation rate from the white bulbs. As was the case in humidity, the rate of evaporation is higher in the heavily thinned stand and lower in the moderately thinned.

Tables 21 and 22 give the statistical constants for these comparisons.

The figures in Table 22 show that the evaporation rate was significantly lower at the surface of the moderately thinned stand than in the

Table 20. Rate of Evaporation in the Three Plots, Monthly Averages

Date	Unthinned				Heavily thinned				Moderately thinned			
	Evaporation, c. c.				Evaporation, c. c.				Evaporation, c. c.			
	Surface		Crown		Surface		Crown		Surface		Crown	
	White	Black	White	Black	White	Black	White	Black	White	Black	White	Black
1933												
July, Monthly mean	11.1	14.3	17.3	25.9	14.3	19.0	20.6	29.4	12.1	13.9	17.3	23.6
August, Monthly mean	12.3	14.2	16.9	22.9	14.9	17.9	20.3	27.0	12.1	13.3	17.0	22.1
September, Monthly mean	6.6	9.8	11.6	16.6	10.4	12.2	15.2	20.7	7.9	8.5	10.8	16.7
Total for season	1,038	1,314	1,581.5	2,271.5	1,601.5	1,982	1,926	2,611.1	1,107	1,260	1,566	2,122.5
1934												
June, Monthly mean	15.7	17.6	24.6	31.6	19.0	22.3	24.7	31.4	14.5	16.5	24.9	29.1
July, Monthly mean	17.4	19.4	26.8	36.2	21.2	25.5	28.1	35.8	16.8	19.1	28.5	33.0
August, Monthly mean	12.5	14.3	22.5	27.8	14.5	17.8	22.3	28.2	10.5	13.5	20.9	25.2
September, Monthly mean	4.4	5.2	9.0	12.3	10.3	6.8	8.9	11.8	3.9	5.3	8.9	12.7
Total for season	1,689.7	1,892.72	800.4	3,577.1	2,054.7	2,439.2	2,850.3	3,558	1,595.4	1,841.9	2,759.8	3,357.4

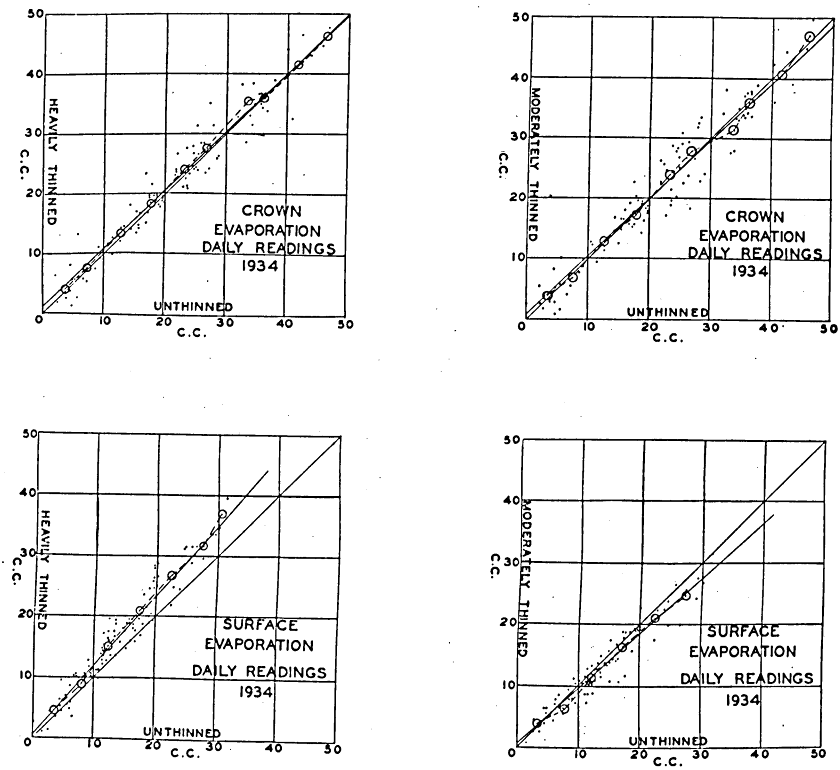

FIG. 7. SCATTER DIAGRAMS SHOWING THE RATE OF EVAPORATION IN THE CROWNS AND AT THE SURFACE OF THE THINNED AND UNTHINNED PLOTS

Table 21. Correlation Coefficients Between Evaporation Rate in Thinned and Unthinned Stands and the Regression Equation Measuring the Relationship

Evaporation rate, c. c.	Correlation coefficient		Linear regression equation	
	Moderately thinned	Heavily thinned	Moderately thinned	Heavily thinned
Crown	+0.957	+0.947	M T = +0.959 U T +0.86	H T = +0.976 U T +1.10
Surface	+0.926	+0.958	M T = +0.886 U T +0.85	H T = +1.146 U T +0.75

Table 22. Differences Between the Means of Evaporation Rate in Thinned and Unthinned Stands and Test of Significance

Evaporation rate, c. c.	Moderately thinned			Heavily thinned		
	Difference of means	Standard error of difference	Ratio	Difference of means	Standard error of difference	Ratio
Crown	−0.03	0.34	0.09	+0.54	0.37	1.15
Surface	−0.63	0.28	2.2	+2.65	0.27	9.8

unthinned at the surface, while in the heavily thinned stand the evaporation rate was higher than in the unthinned stand. The ratio indicates that the difference is highly significant. The difference in evaporation rate between the thinned and unthinned stands at the crown level was not significant.

Light

During the course of the study no accurate instrument for measuring the light intensity was available at this station. Some indication of the difference in light intensity can be secured from the behavior of the black atmometer bulbs when contrasted with the white. To arrive at the complete determination of the differences in light intensity, it would have been necessary to operate a pair of bulbs in full sunlight. To obtain an area of full sunlight would have necessitated the placing of the bulbs at too great a distance from the sets in the thinned stands. Some investigators, as for example Adams (27), have found that the results secured by this method were not consistent enough to allow the computation of light intensity.

The total evaporation from the pair of bulbs for the two seasons is given in Table 20.

While definite values expressing solar radiation cannot be arrived at from the above, the indications are that the light intensities at the surface vary with the degree of thinning, which is more or less axiomatic, but that the light intensities in the crowns do not. The crown figures, however, are not a good indication of conditions as they exist in the crown. The towers were located in the midpoint of the live crown, and the size of the platform necessary for instruments admitted an area of sunlight more than there would otherwise have been. No trees were removed to make way for the tower, however.

Late in the fall of 1934 a Weston Illumination Meter with a photronic cell became available. Dr. H. L. Shirley of the Lake States Forest Experiment Station recommended that a series of readings be taken with this instrument at the first opportunity. Even tho the readings would not give the actual values as found during the growing season, the relationship between the plots would be shown by the readings.

The first absolutely clear day on which it was possible to take readings was February 20, 1935. A reading was taken in the open at the start and at the finish of the observations on the plots. Fifty readings were taken on the check plot and 100 on each of the thinning plots. Ten lines were run across each plot, from west to east. At equal distances on each of these lines, ten readings were taken on the thinned plots and five on the unthinned. As a standard with which to compare the plot readings, the first reading in the open was used for the check plot, an average of the two for the heavily thinned plot, and the last reading for the moderately thinned plot. Since the sun is relatively low at this time of the year and moves rapidly, it was necessary to make the readings in as short a time as possible.

It is possible to get quite a variation in light intensities in any of the stands, depending upon whether or not the individual reading was taken in an open space or under a crown. In the unthinned plot, the readings were varied from 140 foot candles to 1,600 foot candles with an average of 433 foot candles. In the heavily thinned plot, the readings varied from 200 foot candles to 3,400 foot candles and averaged 664 foot candles. In the moderately thinned plot, the readings varied from 140 foot candles to 2,400 foot candles and averaged 356.7 foot candles. Table 23 gives the average reading and the comparison to full sunlight.

Table 23. Light Intensities of the Three Plots Compared to Full Sunlight

Plot	Average light intensity, F.C.*	Full sunlight standard, F.C.	Per cent full sunlight
Unthinned	433	4,200	10.3
Heavily thinned	664	3,300	20.1
Moderately thinned	356.7	2,400	14.8

* F.C. = foot candles.

Naturally the snow would have some effect upon the light intensity, but this was constant for all three plots. Without a doubt, the readings do not give the correct percentage of sunlight. They apparently do show the true relationship of light conditions in the three plots.

It is difficult to judge the full importance of light in thinning practice. Certainly, from many standpoints, the light in the crowns rather than at the surface is the more important. The increased light on the surface is of importance, however, since it affects soil conditions and thus the growth. Moreover, increased light at the surface is accompanied by increased light in the crowns, probably at a much smaller ratio. Beck (1912) states that light is the only manageable factor, a statement that will not bear analysis since soil temperature, air temperature, humidity, and evaporation, all can be influenced by stand density. The true statement of the fact would probably be that difference in light intensity is, at least to a certain extent, an indication of favorable or unfavorable differences in other factors which are at least as important as the light itself.

A reference to the comparison of the crop trees in Table 5 shows the increment during the last five years to be in almost the same proportion as the difference in light intensity.

Soil Temperature

Changes in soil conditions due to thinning are quite as marked as changes in atmospheric factors. To properly evaluate these changes is quite difficult. The underground parts of the tree are equally as important as the aerial parts. The studies of Li (1926) have shown the influence of various types of forest cover upon soil temperature. Stevens (1931), in studying the root growth of white pine, was not able to correlate root growth with climatic conditions. He quotes Engler (1904) who states that the lower temperature limit for root growth of conifers lies at about 5-6° C. (41-43° F). Adams (1934) has shown the importance of soil temperature upon the germination and root development of white pine seedlings.

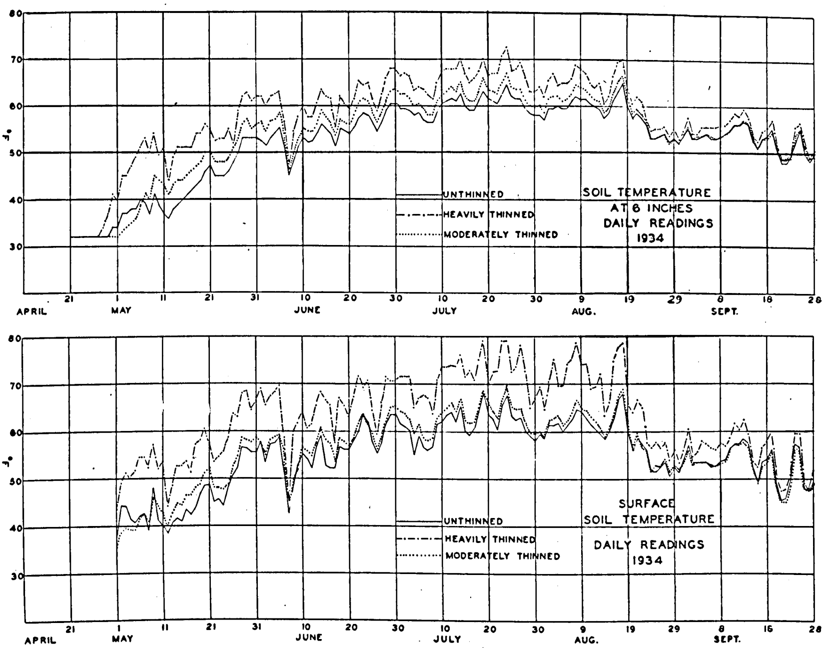

FIG. 8. CHRONOLOGICAL GRAPH OF SOIL TEMPERATURES AT THE SURFACE AND AT SIX-INCH DEPTH FOR THE THREE PLOTS

Soil temperature readings were taken at the surface, 6-, 12-, and 24-inch depths in each of the plots. Adams (1928), in studying the effect of spacing in a jack pine plantation, found that the lateral roots lay in the first foot of soil. He found no tendency towards the production of tap roots. On the light sandy soils of the Cloquet Forest, the production of tap roots in this species is common. Cheyney (1932), in excavating the root system of a jack pine, 10 inches in diameter at breast height, found that the deepest penetration was 5.5 feet and that the bulk of the roots were found in the upper foot of soil. These studies indicate that the important part of the root system lies within the range of soil depths studied.

Figures 8 and 9 show the daily soil temperature at the various depths for the three plots. At each depth the general relationship is the same. The higher soil temperatures are found on the heavily thinned plot, the

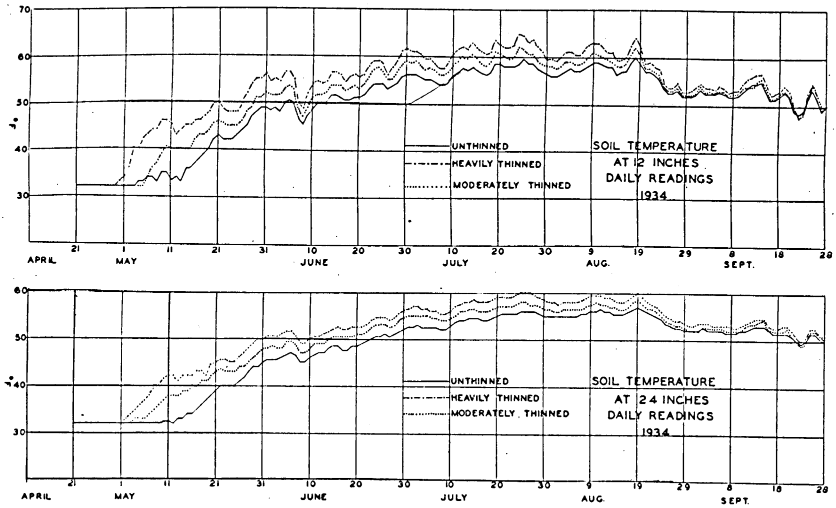

FIG. 9. CHRONOLOGICAL GRAPH OF SOIL TEMPERATURES AT THE 12-INCH AND 24-INCH DEPTHS FOR THE THREE PLOTS

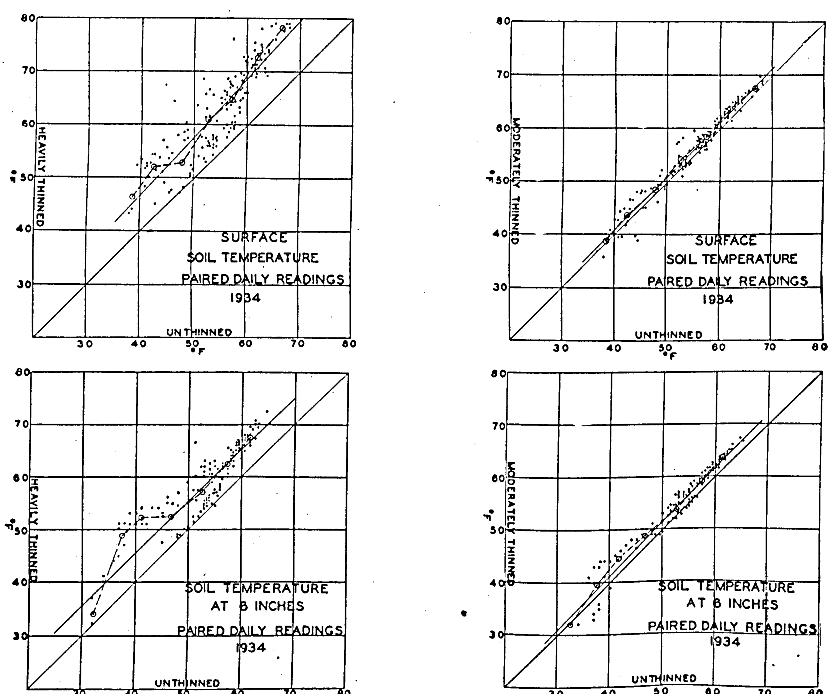

FIG. 10. SCATTER DIAGRAMS OF SOIL TEMPERATURES AT THE SURFACE AND AT SIX-INCH DEPTH FOR THE THINNED AND UNTHINNED PLOTS

lowest on the unthinned. At the beginning of the growing season, a temperature of 32° F. prevailed in the unthinned plot ten days earlier than in the heavily thinned plot. The rise in temperature was much more rapid in the heavily thinned than in the other two plots. At the end of the growing season the soil temperatures tend to approach each other in all the plots.

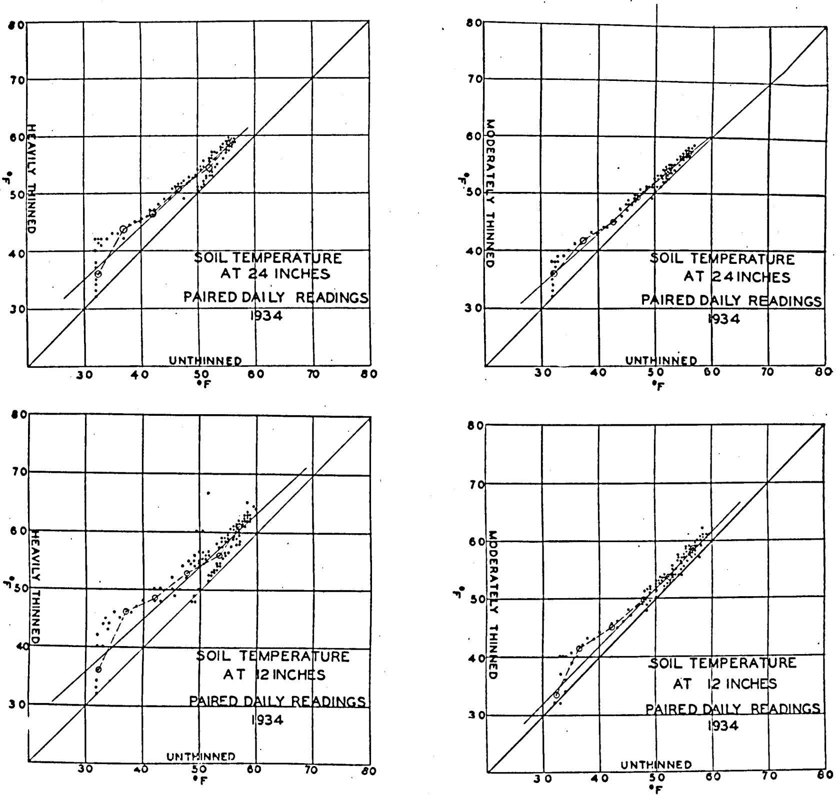

FIG. 11. SCATTER DIAGRAMS OF SOIL TEMPERATURES AT 12-INCH AND 24-INCH DEPTHS FOR THE THINNED AND UNTHINNED PLOTS

If we accept the 12-inch depth as being one in which the bulk of the roots are contained and accept Engler's figure of 41° F. as being the temperature necessary for the start of root growth in conifers, we find that the heavily thinned plot had a growing season 15 days longer and the moderately thinned nine days longer than the unthinned.

The differences in soil temperature are the most marked and clear-cut of any of the factors. Adams (1929) in a similar study found that thinning did not increase the soil temperature at the 6- and 18-inch depths.

The statistical comparison of soil temperatures is given in Figures 10 and 11. In every instance the temperatures were higher in the thinned

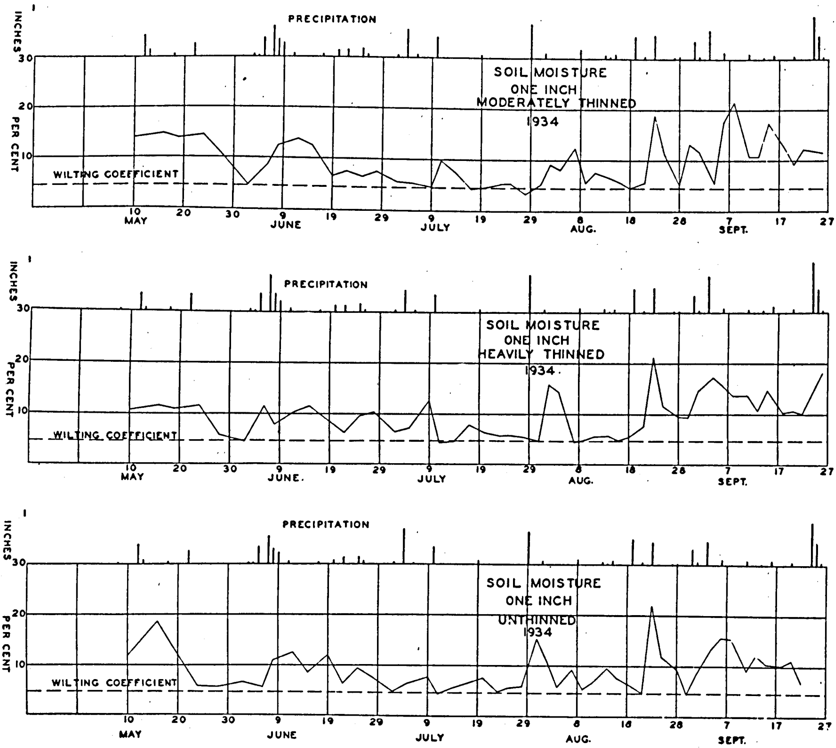

FIG. 12. CHRONOLOGICAL GRAPH OF SOIL MOISTURE AT THE ONE-INCH DEPTH FOR THE THREE PLOTS

plots than in the unthinned. Tables 24 and 25 give the statistical constants for these plots.

Table 24. Correlation Coefficients Between Soil Temperatures of Thinned and Unthinned Stands and the Regression Equation Measuring the Relationship

Soil temperature, ° F.	Correlation coefficient		Linear regression equation	
	Moderately thinned	Heavily thinned	Moderately thinned	Heavily thinned
Surface	+0.970	+0.888	M T = +1.013 U T +0.21	H T = +1.094 U T +2.86
6″ depth	+0.976	+0.929	M T = +1.024 U T +0.28	H T = +0.983 U T +6.23
12″ depth	+0.981	+0.941	M T = +0.985 U T +2.38	H T = +0.913 U T +8.34
24″ depth	+0.918	+0.961	M T = +0.880 U T +7.62	H T = +0.912 U T +7.62

Table 25 shows that the soil temperature is higher in the thinned plots than in the unthinned and that the difference is highly significant. The ratio is higher in the heavily thinned plot, indicating that the soil temperature increases with the severity of thinning. While the effect is felt as far down as the two-foot depth, the difference in soil temperature between the thinned and unthinned stands decreases as the depth increases.

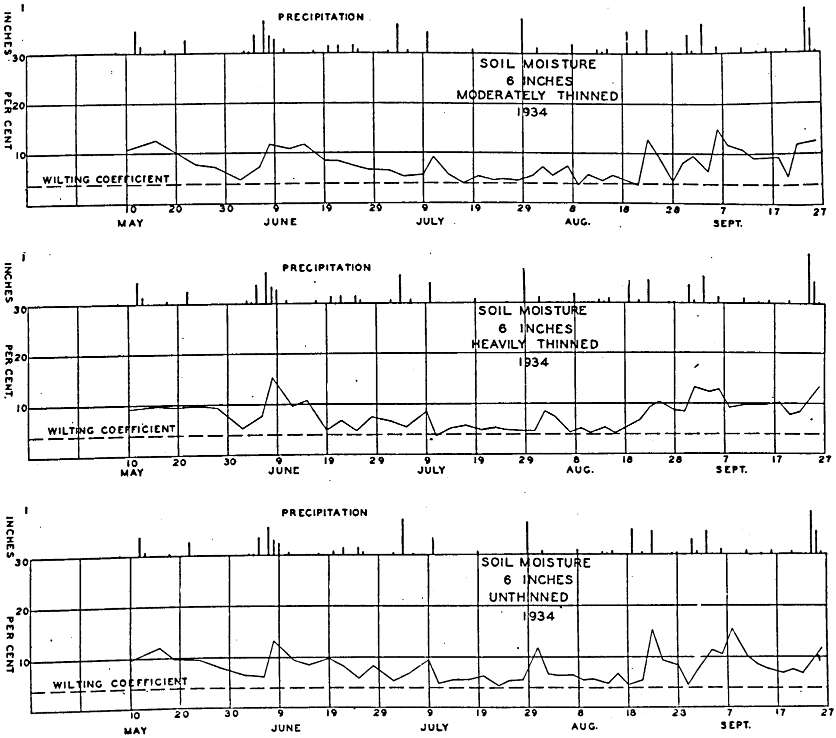

FIG. 13. CHRONOLOGICAL GRAPH OF SOIL MOISTURE AT THE SIX-INCH DEPTH FOR THE THREE PLOTS

Table 25. Differences Between the Means of Soil Temperature in the Thinned and Unthinned Stands and Tests of Significance

	Moderately thinned			Heavily thinned		
Soil temperature, ° F.	Difference of means	Standard error of difference	Ratio	Difference of means	Standard error of difference	Ratio of difference to its standard error
Surface	+0.95	0.15	6.3	+8.04	0.33	24.4
6-inch depth	+1.55	0.16	19.7	+5.33	0.26	20.5
12-inch depth	+1.63	0.13	12.5	+3.99	0.23	17.3
24-inch depth	+1.91	0.27	7.1	+3.43	0.27	12.7

Soil Moisture

Soil moisture is one of the external factors that influences transpiration. Toumey (1928) states that the degree of moisture available at the driest period of the growing season is more important than the average degree of available moisture. In this study the available moisture was determined by the indirect determination of the wilting coefficient, according to the method of Briggs and Schantz (1912). The deter-

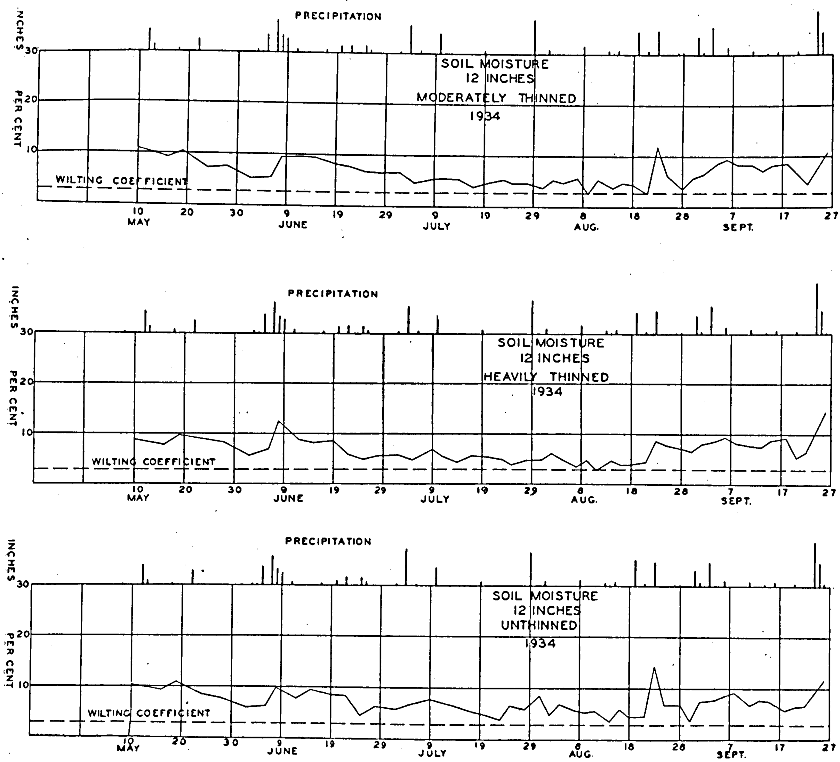

FIG. 14. CHRONOLOGICAL GRAPH OF SOIL MOISTURE AT THE 12-INCH DEPTH FOR THE THREE PLOTS

minations of the moisture equivalents were made through the co-operation of Dr. F. J. Alway, by the Division of Soils of the University of Minnesota Agricultural Experiment Station. They are given in Table 26.

Table 26. Moisture Equivalents of the Three Plots (Average of Three Samples Collected at Different Dates)

Plot	Depth of sample			
	1 inch	6 inches	12 inches	24 inches
Unthinned	8.4	7.5	6.1	3.7
Heavily thinned	8.4	7.3	4.8	2.9
Moderately thinned	8.1	7.2	5.0	3.6
Wilting coefficient, per cent	4.5	3.9	2.8	1.8

The wilting coefficient was determined for all the plots as a unit, since the moisture equivalents showed little variation. The average moisture equivalent was divided by 1.84, which for this purpose should give sufficiently accurate results.

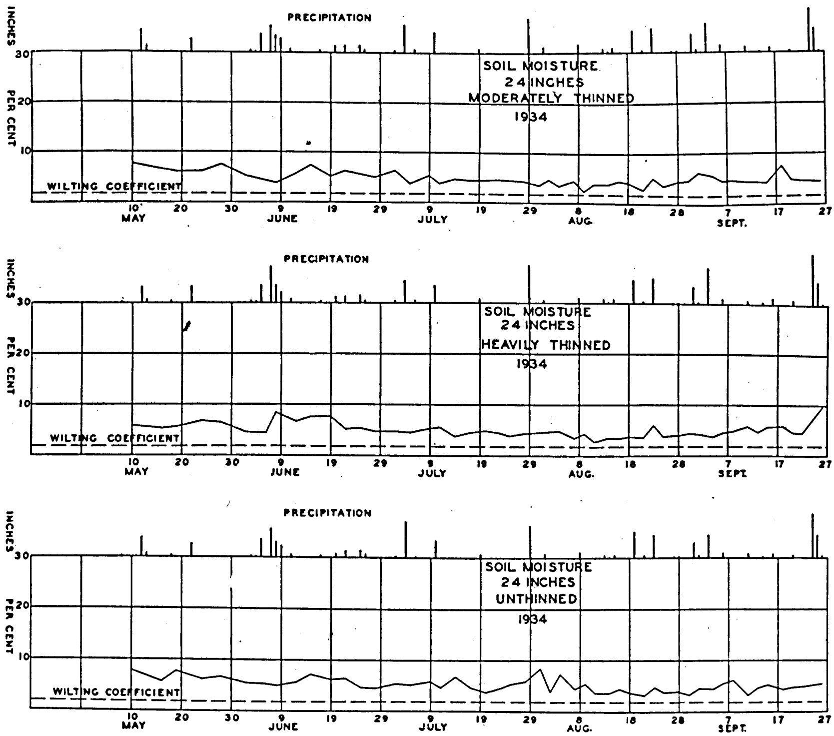

FIG. 15. CHRONOLOGICAL GRAPH OF SOIL MOISTURE AT THE 24-INCH DEPTH FOR THE THREE PLOTS

Figures 12 to 15 show the seasonal trends for soil moisture at the different depths on the three plots. An examination of these graphs shows extreme variations between the plots on the different sampling days. The indications are that thinning had very little effect upon the soil moisture. It should be noted that the moderately thinned and heavily thinned plots dropped near to, or below, the wilting coefficient more often than the unthinned at the 1-, 6-, and 12-inch depths, but at the 2-foot depth there was little difference. This is probably due to the heavier ground cover and the larger crown development of the thinned plots.

Figures 16 to 19 show the statistical comparison of the soil moisture for the different depths for the two seasons. In this instance the data for the two seasons were used because the results were apparently opposite. The plotting of the paired readings shows that the soil moisture was higher in the thinned plots than in the unthinned in 1933 but lower in 1934. Tables 27 and 28 give the statistical constants for the soil moisture.

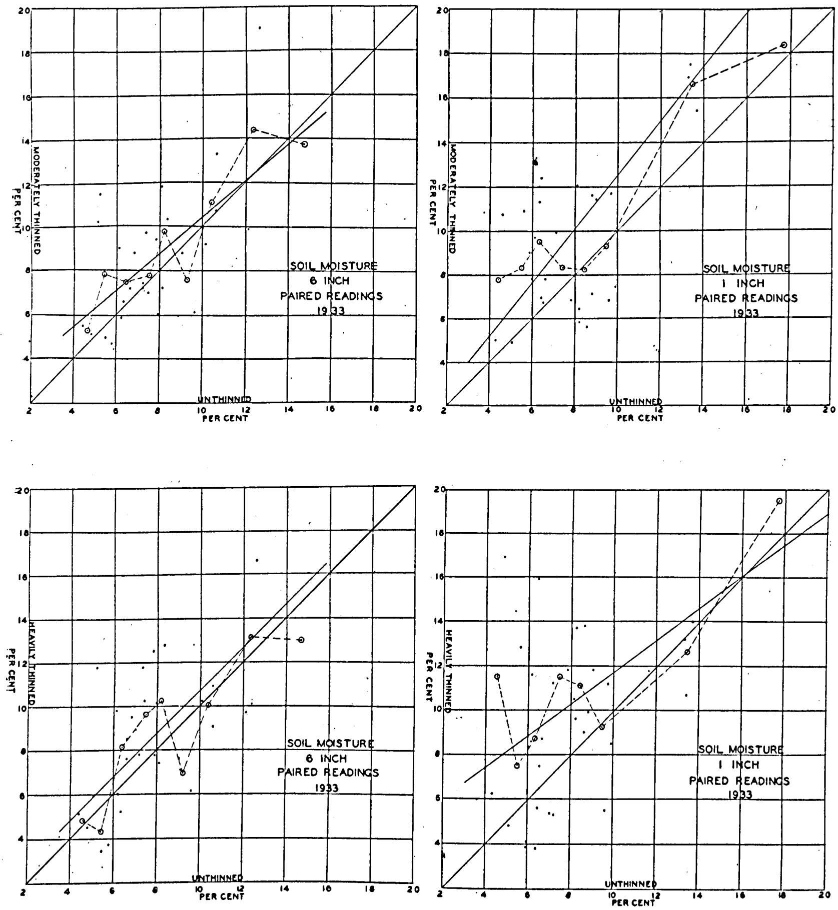

Fig. 16. Scatter Diagrams of Soil Moisture at the One-inch and Six-inch Depths for the 1933 Season in the Thinned and Unthinned Plots

Table 27. Correlation Coefficients Between Soil Moisture in Thinned and Unthinned Stand and the Regression Equation Measuring the Relationship

Soil moisture	Correlation coefficient		Linear regression equation	
	Moderately thinned	Heavily thinned	Moderately thinned	Heavily thinned
1933				
1″ depth	+0.727	+0.578	M T = +1.224 U T +0.31	H T = 0.718 U T +4.53
6″ depth	+0.657	+0.784	M T = +0.828 U T +2.18	H T = 0.984 U T +0.87
12″ depth	+0.372	+0.371	M T = +0.371 U T +4.51	H T = 0.511 U T +3.68
24″ depth	+0.096	+0.170	M T = +0.143 U T +3.66	H T = 0.275 U T +3.42
1934				
1″ depth	+0.638	+0.549	M T = +0.529 U T +4.53	H T = 0.599 U T +3.93
6″ depth	+0.702	+0.609	M T = +0.725 U T +1.87	H T = 0.622 U T +2.80
12″ depth	+0.769	+0.722	M T = +0.807 U T +0.92	H T = 0.778 U T +1.20
24″ depth	+0.322	+0.337	M T = +0.319 U T +3.22	H T = 0.366 U T +3.06

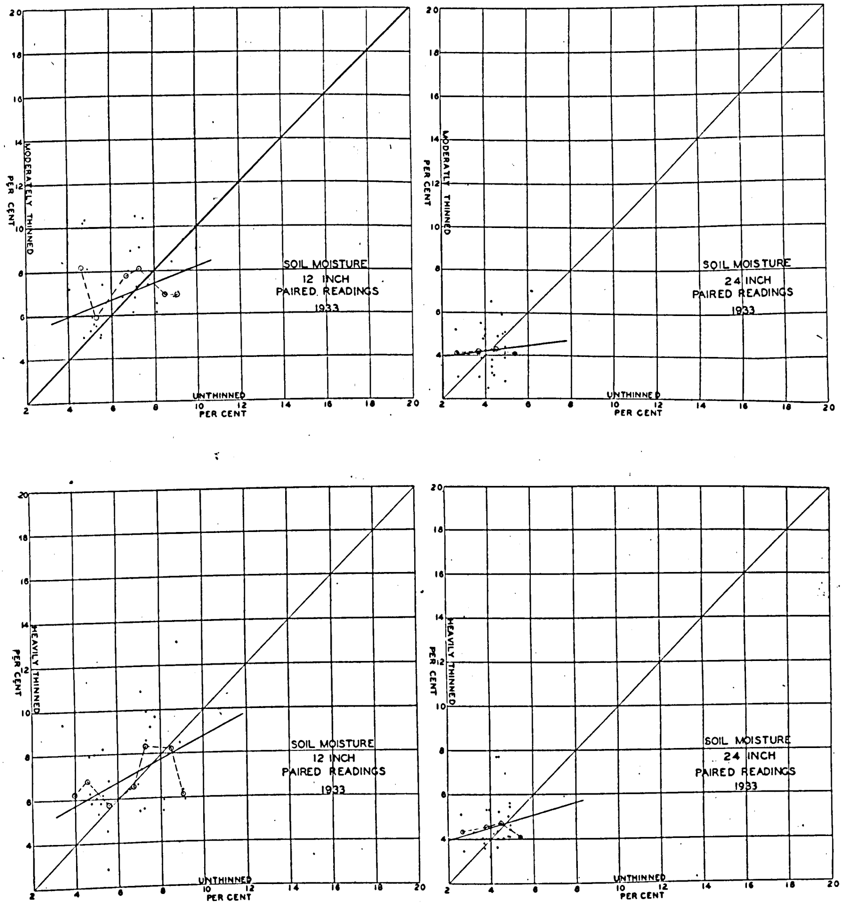

FIG. 17. SCATTER DIAGRAMS OF SOIL MOISTURE AT THE 12-INCH AND 24-INCH DEPTHS FOR THE 1933 SEASON IN THE THINNED AND UNTHINNED PLOTS

Table 28 shows that the differences of the means were all plus in 1933 (that is, the soil moisture of the thinned stands was higher) and minus in 1934, except in the case of the surface inch. The 1933 differences are significant only in the case of the surface inch and at the 6-inch depth in the heavily thinned stand, while in 1934 the difference is significant only at the 12-inch depth for the moderately thinned stand.

The important point is the difference in relationship between the two seasons. There exists a possible explanation of this fact. Table 12 shows the leaf area, and consequently the transpiration possibilities, to be greater in the thinned plots than in the unthinned in 1934. The loss in leaf area due to a sleet storm in April 1934, both in actual needles and in buds which would produce new needles, was much heavier in the unthinned stand, as shown in Table 38. If this loss had not

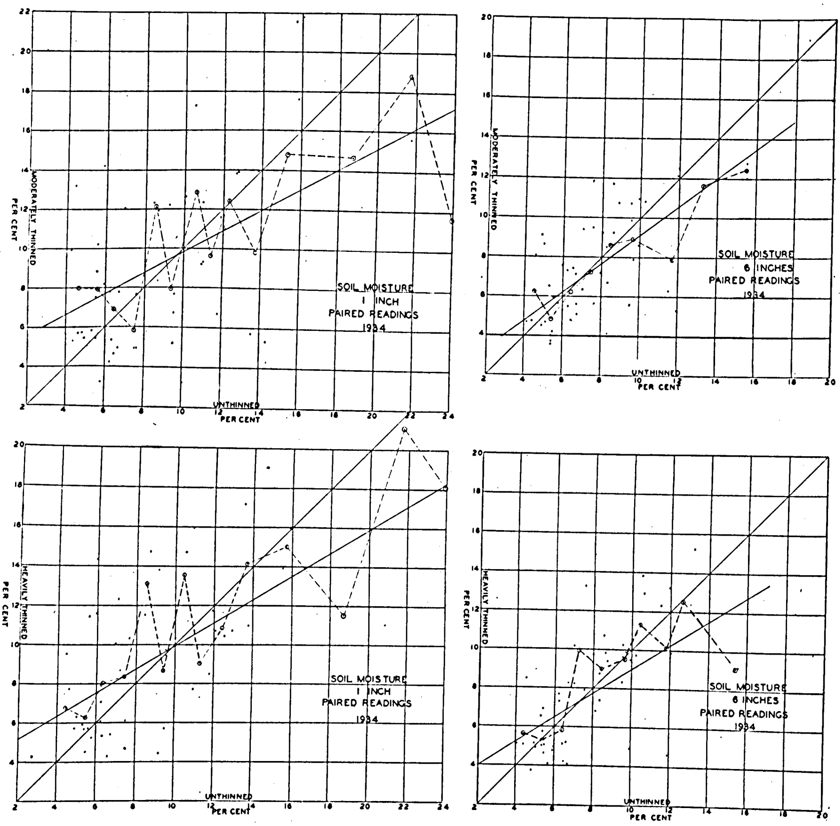

FIG. 18. SCATTER DIAGRAMS OF SOIL MOISTURE AT THE ONE-INCH AND SIX-INCH DEPTHS FOR THE 1934 SEASON IN THE THINNED AND UNTHINNED PLOTS

Table 28. Differences Between the Means of Soil Moisture in the Thinned and Unthinned Stands and Test of Significance

Soil moisture	Moderately thinned			Heavily thinned		
	Per cent difference of means	Standard error of difference	Ratio of difference to its standard error	Per cent difference of means	Standard error of difference	Ratio of difference to its standard error
1933						
1-inch depth	+2.21	0.72	3.1	+2.14	0.64	3.3
6-inch depth	+0.82	0.43	1.9	+0.74	0.35	2.1
12-inch depth	+0.42	0.31	1.4	+0.50	0.38	1.3
24-inch depth	+0.08	0.21	0.4	+0.38	0.22	1.7
1934						
1-inch depth	+0.11	0.53	0.2	+0.16	0.59	0.3
6-inch depth	−0.32	0.31	1.0	−0.20	0.35	0.6
12-inch depth	−0.45	0.21	2.0	−0.43	0.24	1.8
24-inch depth	−0.27	0.21	1.3	−0.27	0.22	1.2

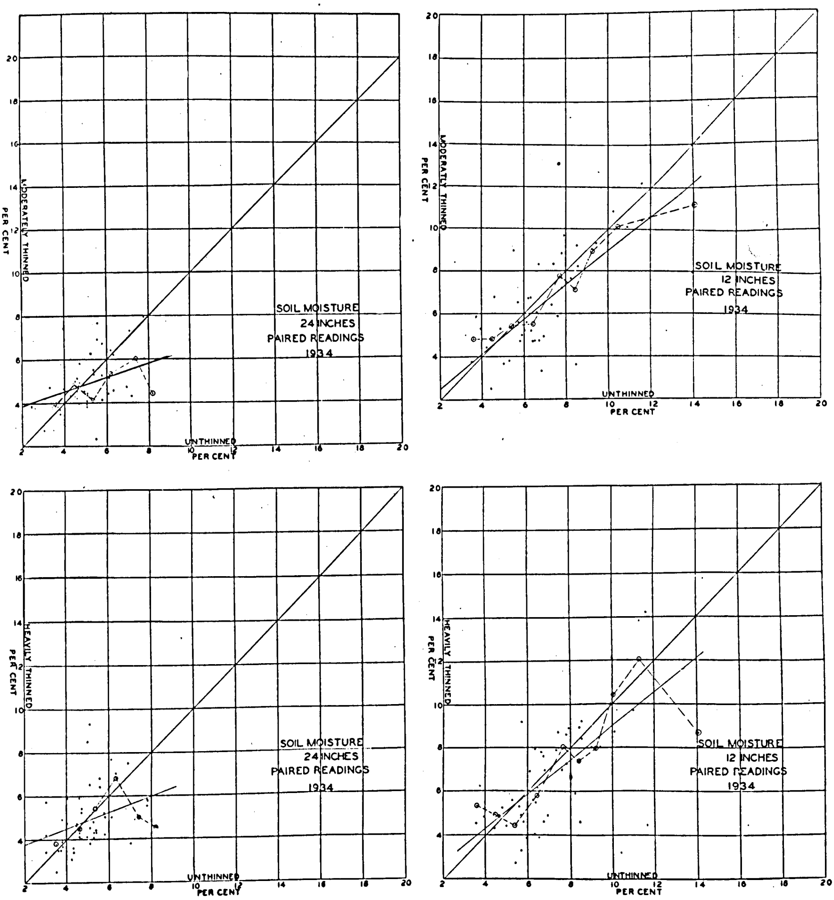

FIG. 19. SCATTER DIAGRAMS OF SOIL MOISTURE AT THE 12-INCH AND 24-INCH DEPTHS FOR THE 1934 SEASON IN THE THINNED AND UNTHINNED PLOTS

occurred, it is probable that the leaf area for the unthinned plot might have been larger than for the thinned. If this supposition be true, then there was present a larger leaf area in the unthinned stand in 1933. Unfortunately, there is no method by which this can be checked, but it does seem a plausible explanation of the differences.

Humus Conditions

Carbonnier (1933) maintains that one of the most important effects of thinning is the reaction that the increased light may have upon the condition of the humus. In fairly moist climates, the rate of decomposition can be speeded up, while under more arid conditions it can be retarded. Möller (1931) maintains that thinnings are helpful in preventing the formation of raw humus. Hesselman (1925) maintains that thinnings, by increasing the light and soil temperature, may cause a more rapid nitrification and thereby increase the plant food available. The study of the effect of thinning upon the soil is an extremely complicated problem and one that warrants separate attention. The indications of this study are that the most striking and clear-cut changes in the environmental factors due to thinning occur in the soil temperature.

An examination of the humus conditions made by the writer and Dr. F. J. Alway of the Division of Soils, University of Minnesota, seemed to indicate that there was a much more rapid decomposition of the litter in the heavily thinned plot than in the unthinned. The litter in the unthinned plot apparently showed a tendency to form raw humus, as indicated by the mycelium present. It would be called a Fibrous Mor according to the classification of Romell and Heiberg (1931). The humus in the heavily thinned stand showed no mycelium present, and altho its classification would probably be the same as the unthinned, the casual preliminary examination seemed to indicate that it was in much better condition.

In co-operation with Dr. Alway, samples were collected from six plots one foot wide and ten feet long on each of the three plots. The undergrowth was removed and saved, the litter and duff collected, and the samples of the top three inches of mineral soil were taken. Table 29 gives the average oven-dry weights for the various samples.

Table 29. Oven-dry Weights of Forest-Floor Samples from the Three Plots Collected Ten Years After Thinning (Determinations by A. Hawkinson and Gerda Bergata)

Plot	Undergrowth, grams	Litter and mor, grams	Leaf mold, grams
Unthinned	51	2,188	10,640
Heavily thinned	146	2,134	11,145
Moderately thinned	184	1,688	10,889

Two facts are brought out by these figures. The first is the larger amount of undergrowth present in the two thinned plots as a result of the increased light. The second is the larger amount of leaf mold present in the thinned plots. While the difference is not large, it nevertheless indicates a little more rapid decomposition under the conditions created by the thinning. Kittredge (1929) has pointed out that the rate of change in forest soils is slow, often extending over a period of hundreds of years, but that some changes do occur in periods of from 10 to 20 years. If there were a more rapid decomposition of the duff and litter, it should be reflected in a lower degree of acidity. Table 30 gives the average pH concentration and cH (active acidity) of the samples of the various plots.

Table 30 shows that there is no significant difference in the acidity of the forest floor of the three plots. Hesselman (1925) maintains that acidity alone is not an indication of unhealthy soil conditions. As based on these figures, the thinning apparently has had, as yet, little effect upon the acidity.

Table 31 gives the composition of the forest floor of the three plots as determined by the Division of Soils of the University.

Table 30. Hydrogen-ion Concentration of Forest-Floor Samples from the Three Plots, Samples not Allowed to Become Air-dried (Determinations by R. M. Pinckney)

Plot	Sample no.	Litter and duff pH	Leaf mold pH	Surface 3 inches of soil pH	Litter and duff cH	Leaf mold cH	Surface 3 inches of soil cH
Heavily thinned	1	5.19	4.95	5.10	63	100	80
	2	4.90	4.45	4.75	125	315	160
	3	4.70	4.70	5.05	200	200	80
	4	4.64	4.55	4.90	250	250	125
	5	4.72	4.99	5.48	200	100	33
	6	5.20	4.94	5.06	63	125	80
Unthinned	7	4.72	4.82	5.17	200	160	63
	8	4.82	4.92	5.20	160	125	63
	9	5.20	5.14	5.25	63	80	50
	10	5.15	4.97	4.97	63	100	100
	11	5.10	4.85	5.25	80	125	50
	12	5.09	5.30	4.85	80	50	125
Moderately thinned	13	5.40	4.80	4.88	40	160	125
	14	5.10	4.31	4.30	80	500	500
	15	5.35	5.27	5.28	40	50	50
	16	5.37	5.25	5.60	40	50	25
	17	5.32	4.98	5.18	50	100	63
	18	4.96	5.17	5.17	100	63	63

cH = active acidity.

Table 31. Composition of Forest Floor from the Three Plots

		Heavily thinned	Moderately thinned	Unthinned
"F" layer	Ash per cent	25.80	17.40	16.80
"H" layer	Ash per cent	89.16	85.83	82.30
"F" layer	Organic matter per cent	74.20	82.60	83.20
"H" layer	Organic matter per cent	10.84	14.17	17.76
"F" layer	Lime (CaO) per cent	0.87	0.82	0.83
"H" layer	Lime (CaO) per cent	0.29	0.32	0.37
"F" layer	pH value	4.8	5.2	5.0
"H" layer	pH value	4.7	4.8	5.0
"F" layer	Active acidity (cH)	150	58	108
"H" layer	Active acidity (cH)	182	154	106
"F" layer	Nitrogen per cent	0.98	1.10	1.06
"H" layer	Nitrogen per cent	0.22	0.25	0.34

There is evident a little more rapid decomposition of the litter in the heavily thinned plot as shown by the larger proportion of ash in both the "F" and "H" layers. The analysis is based on a composite of all the samples, the acidity of which is given in Table 30. The lime content is higher in the litter of the heavily thinned plot and lower in the leaf mold. In nitrogen content, there is a difference between the heavily thinned and the unthinned stands. Theoretically, at least, conditions should be more favorable for nitrification in the heavily thinned plot.

The amount of litter that reaches the forest floor annually is an important factor in considering its behavior. The thinning, by reducing the number of trees, would, of course, reduce the amount of litter that falls. The reduction in number of trees would in time be compensated for by the increased crown development of the trees in the thinned plot. Table 32 shows the fall per acre for the three plots during the period of June 15 to November 1, 1934.

Table 32. Weight of Litter, Pounds Per Acre Falling on the Three Plots Between June 15 and November 1, 1934

(Determinations by Division of Soils)

Plot	Moist weight, pounds/acre	Dry weight, pounds/acre	Per cent moisture	Per cent ash	Per cent nitrogen
Unthinned	4,051	2,788	30.0	16.95	0.55
Heavily thinned	2,936	2,047	30.1	33.44	0.44
Moderately thinned	2,845	2,134	25.3	13.86	0.47

Table 32 shows that on the basis of dry weight the amount of litter that falls is proportional to the density of the stand. The heavy thinning reduced the original number of trees by 69 per cent, leaving a stand that was only 25 per cent of the number in the unthinned and which, because of the loss in numbers in the unthinned, had increased to 37 per cent at the time of collection of the litter. The fall of litter on the basis of dry weight was only 26 per cent greater on the unthinned than on the heavily thinned.

Alway and Zon (1930) found the fall of litter in a 30-year jack pine stand on the Cloquet forest to be 2,319 pounds for an entire year. The stand in which they collected the litter was more open than that in which the three plots studied are located. This is reflected in the somewhat smaller fall of litter which they secured as compared with the unthinned stand of this study.

The nitrogen per cent is less in the heavily thinned plot than in the unthinned. A reference to Table 32 shows the same to be true for the forest-floor samples. A variation does exist where the litter and mor of the moderately thinned plot shows essentially the same nitrogen per cent as the unthinned.

To check this, five samples of freshly fallen litter, weighing approximately 200 grams each, were collected at random in each plot. Nitrogen determinations were made. Table 33 shows the results. The results of the analysis confirm the previous results in showing that the nitrogen per cent is higher in the unthinned stand than in the thinned.

Table 33. Average Nitrogen Per Cent of the Random Litter Samples from the Three Plots

(Determinations by Division of Soils)

Plot	Average nitrogen per cent
Unthinned	0.72
Heavily thinned	0.60
Moderately thinned	0.65

When the various sample trees were cut for analysis, the needles on each tree were carefully stripped from the branches and saved to determine the relative weight of the needles in the various crown classes. To determine whether or not the difference in nitrogen per cent, as shown in the litter, was reflected in the individual tree, nitrogen determinations were made of the needles. Table 34 shows the results secured from this analysis.

Table 34. Nitrogen Per Cent in Needles and Grams of Nitrogen 40 Per Thousand Needles of the Trees in Various Crown Classes on the Three Plots

(Determinations by Division of Soils)

Crown class	Unthinned		Heavily thinned		Moderately thinned	
	Average nitrogen, per cent, dry weight	Nitrogen, grams per 1,000 needles	Average nitrogen, per cent	Nitrogen, grams per 1,000 needles	Average nitrogen, per cent	Nitrogen, grams per 1,000 needles
Dominant	1.18	0.090	1.23	0.113	1.29	0.102
Codominant	1.32	0.111	1.25	0.100	1.31	0.095
Intermediate	1.36	0.109	1.29	0.073	1.39	0.078
Suppressed	1.36	0.124	....	....	....	....
Trees of 3.3-inch diameter in 1924	1.37	0.111	1.25	0.100	1.31	0.095

Except for the dominant class, the nitrogen per cent is higher in the unthinned than in the heavily thinned. The percentage becomes increasingly larger in the lower crown classes, progressing at a more rapid rate in the unthinned than in the thinned. Since the lower crown classes are more prominent in the unthinned, it would, of course, tend to show a larger nitrogen percentage in the fresh litter. Whether or not this is of any significance in considering the productivity of the soil, only more detailed soil studies will show. These findings are somewhat at variance with those of Adams (1928) who found that the jack pine growing in a 2x2 spacing had a smaller nitrogen content than those growing in the wider spacings.

Summary of Environmental Factors

While the differences in conditions are best studied on the basis of daily comparisons, nevertheless a summary of seasonal conditions can give valuable information. These summations can show whether temperatures were higher or lower on the unthinned, whether there was a difference in the humidity and evaporation. It is recognized that daily fluctuations have a tremendous influence upon the activities of the tree. Just how to determine the effect of these fluctuations on the growth of the tree is difficult, if not impossible, at present. The growth of the tree is, however, the result of the total season's conditions. This is especially true of indigenous species, that through the centuries have adapted themselves to the fluctuations that occur in any region.

The summations of air temperature, total above 40° F.; soil temperature, above 32° F.; relative humidity, total per cent; evaporation, total cubic centimeters from white bulbs; precipitation, total inches, and soil moisture, total per cent, are given in Table 35 for the 1934 season. Comparisons are made between the surface and the crown and between the thinned and unthinned plots.

Table 35. Summation of Environmental Factors in the Three Plots for 1934: Air Temperature, Total Above 40°F.; Soil Temperature, Total Above 32°F.; Relative Humidity, Total Per Cent; Evaporation, Total Cubic Centimeters, and Soil Moisture, Total Per Cent

Factor	Unthinned	Heavily thinned	Condition after thinning	Moderately thinned	Condition after thinning
Air temperature					
Crown	3,175	3,143.7	0.9% cooler	3,149.8	0.8% cooler
Surface	3,071.2	3,188.2	3.8% warmer	3,197.0	4.0% warmer
Per cent difference from crown	3.2% cooler	1.3% warmer		1.5% warmer	
Soil temperature					
Surface	24,858.5	28,506	14.6% warmer	25,290	1.7% warmer
6-inch	3,264	4,144.5	23.8% warmer	3,604	10.4% warmer
12-inch	2,764.5	3,495.0	26.4% warmer	3,238	17.1% warmer
24-inch	2,406	3,085.5	28.2% warmer	2,831	17.6% warmer
Per cent decrease with depth					
12-inch	15.3%	15.0%		10.1%	
24-inch	26.2%	25.5%		21.4%	
Relative humidity					
Crown	28,668.5	28,539.5	0.4% lower	28,968	1.0% higher
Surface	29,261.5	28,945.0	1.0% lower	29,659	1.3% higher
Per cent difference from crown	2.0% higher		1.4% higher	2.4% higher	
Evaporation					
Crown	2,800.4	2,850.3	1.4% greater	2,759.8	1.4% less
Surface	1,689.7	2,054.7	21.5% greater	1,595.4	5.5% less
Per cent difference from crown	43.6% less	28.2% less		42.2% less	
Precipitation total	8.15	9.10	11.6% greater	8.81	8.1% greater
Soil moisture					
1-inch	460.52	469.97	2.16% wetter	465.74	1.13% wetter
6-inch	388.98	381.21	1.98% drier	374.74	1.66% drier
12-inch	341.85	324.63	5.05% drier	320.63	6.2 % drier
24-inch	249.38	241.82	3.0 % drier	237.00	4.9 % drier

The findings for the two seasons were in general agreement, except in the case of soil moisture. The percentages varied, however. This may be due in part to the fact that the 1933 season's records did not cover a complete growing season.

The air temperature was somewhat cooler in the crowns after thinning and warmer at the surface. In the unthinned stand, the surface temperature was cooler than in the crown, while in the heavily thinned, it was warmer. These results agree with those secured by Adams (1930).

The soil temperature was warmer in the heavily thinned stand than in the unthinned at all depths, the percentage difference being almost constant for all depths. This is the reverse of Adam's findings.

The evaporation was greater in the crowns of all three plots than at the surface and greater in the thinned plots than in the unthinned. The difference between the surface and crown was less in the heavily thinned plot than in the unthinned.

The precipitation reaching the ground was greater in the thinned plots than in the unthinned.

Soil moisture showed a variation between the two seasons. In 1933 the thinned plots showed a higher total soil moisture per cent and in 1934, a lower. The differences as shown by the percentage figures are significant in some cases, as shown by the ratios in Table 28.

On the basis of these summations, the thinned plots showed conditions more favorable to growth. The greater evaporation would probably not be a detriment, since the soil moisture seldom fell low enough to be a limiting factor. The increased soil temperature would promote root activity and possibly stimulate the rate of development and quantity of roots produced. These changes should be and are reflected in a more rapid rate of growth in the thinned plots.

That the growing season is longer in the heavily thinned plots is indicated by the time at which the buds burst and leafing out begins. In the 1934 season, the buds began bursting on the trees of the heavily thinned plot the first week of May, while in the unthinned plot, they did not begin bursting until the beginning of the third week of May. The moderately thinned plot fell half way between. Leafing out was correspondingly earlier in the thinned stands.

Indirect Effect of Precipitation

On the night of April 2, 1934, a rainstorm of 0.46 inch occurred. The temperature dropped to 31° F., and the limbs and twigs became coated with ice. On April 3 and 4, the temperature rose to a maximum of 35° F. for a brief period, not sufficiently long to bring about any thawing. Heavy northeast winds caused considerable movement of the crowns of the trees. The heavy coating of ice present was responsible for the breaking off of a great number of the ends of twigs, carrying with them the needles. The loss of a considerable leaf area inevitably will reduce the growth rate. A superficial examination of the three plots showed that the loss was evidently much greater in the unthinned stand than in the thinned. To check this observation, 10 milacre quadrats were laid out in each of the three plots, and the twigs with the needles were collected from the surface of the snow where they had fallen. The air-dry weights were secured, the proportion of the twigs to the needles determined, and the length and diameter of the needles measured.

Table 36. Weight in Pounds of Needles and Twigs Lost in the Storm of April 3

Plot	Air-dry weight, pounds per acre	Weight of needles, pounds per acre	Weight of twigs, pounds per acre	Needles, per cent
Unthinned	30.5	22.57	7.93	1.42
Heavily thinned	16.11	12.24	3.87	1.35
Moderately thinned	20.50	15.58	4.92	1.24

The figures in Table 36 show that the loss in the unthinned plot was almost twice that of the heavily thinned and one-third more than in the moderately thinned plot.

Three samples of needles, numbering approximately 1,000 each, from each of the three plots were weighed, 100 needles were measured for length, and 50 needles for diameter. The number of needles lost per acre was computed from these figures. The figures are given in Table 37.

Table 37. Number of Needles and Leaf Area Lost Per Acre in the Three Plots and Size of the Needles

Plot	Number needles lost per acre	Length of needles, mm.	Diameter, mm.	Area of needle, sq. mm.	Leaf area lost per acre, sq. m.
Unthinned	10,769,900	35.6	0.573	52.4	564.3
Heavily thinned	6,387,800	32.3	0.616	51.6	329.6
Moderately thinned	7,615,200	33.8	0.572	49.7	378.5

The needles in the heavily thinned plot were shorter and thicker than in the unthinned or moderately thinned. They had more the character of the so-called sun leaves. The area of the needles was figured by the formula suggested by Korstian (1921) $A - L \times (\pi R + 2R)$. It is admitted that the results of this formula are only approximate. They do serve to show that the loss in leaf area in this instance was heavy enough to be a serious factor in the rate of growth of the tree.

The effect of the thinning in minimizing the damage is clearly shown by the smaller leaf area lost.

SUMMARY AND CONCLUSIONS

Very little work has been done on the changes in all environmental factors brought about by thinning. The present study is an analysis of the changes in habitat factors on two plots thinned at different degrees in 1925 and an unthinned check. Remeasurement of the plots in 1929 and 1934, together with an analysis of sample trees in 1934, serves as a basis for a study of changes in rate of growth due to thinning.

1. Jack pine is an important species from a commercial standpoint and from the forester's standpoint in Minnesota.

2. By proper silvicultural methods, the quality of the product can be improved and the yield increased.

3. The stand in which the plots were established was an overdense stand, 27 years old at the time of thinning. The number of trees varied from 3,040 to 2,230 trees per acre in the moderately thinned plot.

4. In the heavily thinned plot, 768 trees per acre were left after thinning. In the moderately thinned plot, 1,105 trees per acre were left.

5. The standard deviation of the diameters on the plot indicates crowding. The increase of the standard deviation in 1934 indicates that the trees are beginning to respond to the thinning.

6. The volume increase was greater on the heavily thinned plot when all the trees were considered, but the advantage at the end of the first period was not significant. At the end of the second period, the difference was significant.

7. When equal numbers of crop trees in all three plots are considered, the rate of growth was much more rapid on the heavily thinned plot.

8. There has been a greater increase in size of corresponding diameter classes on the heavily thinned plot.

9. The intermediate and codominant crown classes showed the greatest response to thinning.

10. The loss in numbers of trees on the check plot occurred almost entirely in the 1- and 2-inch diameter classes.

11. The cubic foot increment was greater during the first five-year period following thinning than during the second. The decrease was greatest in the unthinned stand. An analysis of weather records showed much more favorable weather for growth during the first five-year period than during the second five-year period.

12. The analysis of the individual trees showed that the largest increase in rate of growth following thinning occurred in the codominant and intermediate crown classes.

13. The crown development of the trees in the heavily thinned plots was much greater than on the unthinned. A computation of total leaf area for the three plots showed that the thinned plots had a much larger leaf area than the unthinned, in spite of the smaller number of trees.

14. The mean air temperature was significantly lower in the crowns of the heavily thinned stand and higher at the surface. The difference between the moderately thinned and the unthinned stand was not significant statistically.

15. Individual storms showed a considerable variation in the amount of precipitation reaching the ground. Contrasted with the open, more precipitation reached the ground in the thinned stands than in the unthinned. Taking the 1934 growing season as a whole, 11.6 per cent more precipitation reached the ground in the heavily thinned stand than in the unthinned and 8.1 per cent more in the moderately thinned stand.

16. The relative humidity was higher in the moderately thinned stand than in the unthinned. The difference was highly significant at the surface. In the heavily thinned stand, the humidity was lower than in the unthinned, but the difference was not significant.

17. The rate of evaporation was less in the moderately thinned stand than in the unthinned. At the surface the difference was significant. In the heavily thinned stand, the rate of evaporation was higher. The difference was highly significant at the surface.

18. Differences in the rate of evaporation between black and white atmometer bulbs showed a considerably larger proportion of light per cent in the thinned stands. Light readings taken in the winter showed that the moderately thinned stand had 50 per cent more light than the unthinned, and the heavily thinned stand had 100 per cent more.

19. Soil temperatures were significantly higher in the thinned plots at all depths. The difference decreased with increasing depths. In the heavily thinned stand, a soil temperature that would permit the active development of roots was reached ten days earlier than in the unthinned.

20. The soil moisture was higher in the thinned stands in 1933 and lower in 1934 than in the unthinned stand. Except at the 1- and 6-inch depths, the differences were not significant in 1933. In 1934 the difference was significant only at the 12-inch depth in the moderately thinned stand.

21. There was apparently no change in acidity in the humus, altho the forest floor of the heavily thinned plot seemed to be in much better condition

22. The nitrogen per cent based on dry weight was higher in the "F" and "H" layers of the unthinned stand than in the heavily thinned stand. The freshly fallen litter showed the same relationship as did the needles picked from the trees of the lower crown classes.

23. The difference in soil moisture is explainable in part by the abnormal loss in leaf area as the result of a sleet storm in April 1934. The loss was much heavier in the unthinned stand than in the thinned stands.

24. The thinning made in 1925 resulted in a marked increase in rate of growth. The increase was roughly in proportion to the increased light. In all probability, the increased light was not responsible for the increased growth rate, but it serves as an indication of changes in other factors.

25. The most significant changes occurred in the soil temperatures.

LITERATURE CITED

AALTONEN, V. T. (1926) On the Space Arrangement of Trees and Root Competition. Jour. Forestry, 24:627-644.

ADAMS, W. R. JR. (1928) Effect of Spacing in a Jack Pine Plantation. Bul. 282, Vermont Agricultural Experiment Station.

————. (1930) The Change in Environmental Factors Caused by Thinning in Pine Plantations. Bul. 310, Vermont Agricultural Experiment Station.

————. (1934) The Influence of Soil Temperature on the Germination and Development of White Pine Seedlings. Bul. 379, Vermont Agricultural Experiment Station.

ALBERT, DR. (1915) Ungünstiger Einfluss einen zu Grossen Stamzahl auf den Wasserhaushalt Geringer Kiefernboden. Ztschr. Forst U Jagdw., 47:241-248.

ALWAY, F. J., and ZON, RAPHEAL. (1930) Quantity and Nutrient Contents of Pine Leaf Litter. Jour. Forestry, 28:715-727.

AMILON, J. (1910) Om Tiden för Diametervillväxtens Början hos Barrträden och Orsakerna Härtill. Skogevårdsför. Tidskr., 8:41-56.

BALDWIN, HENRY, I. (1931) The Period of Height Growth in Some Northeastern Conifers. Ecology, 12:665-689.

BATES, CARLOS G., and ZON, RAPHAEL. (1922) Research Methods in the Study of Forest Environment. U.S.D.A. Bul. 1059.

————. (1923) Physiological Requirements of Rocky Mountain Trees. Jour. Agric. Research, 24:97-163.

BEAL, H. W. (1934) The Penetration of Rainfall Through Hardwood and Softwood Forest Canopy. Ecology, 15:412-415.

BECK, DR. (1912) Das Licht als Produktions Factor in der Forstwirtschaft. Tharandter Forstlich Jahrbuch [Review in Forestry Quart. (1913) 11:257-263].

BOUYOUCOS, GEORGE J. (1916) Soil Temperature. Tech. Bul. 26, Michigan Agricultural College Experiment Station.

BOYSEN-JENSEN, P. (1929) Studier over Skovtraeernes Forhold til Lyset. Dansk Skovforen. Tidskr., 14:5-31.

BÖHMERLE, CARL. (1905) Bewasserungeversuche im Walde. Original reference not seen. (Heck, C. R.) Freien Durchforstung.

BRIGGS, LYMAN J., and SHANTZ, H. L. (1912) The Wilting Coefficient for Different Plants and its Indirect Determination, U.S.D.A., B.P.I. Bul. 236.

————, ————. (1917) Comparison of the Hourly Evaporation Rate of Atmometers and Free Water Surface with the Transpiration of *Medicago sativa*. Jour. Agr. Research, 9:277-292.

BURNS, C. P. (1918) Weather Conditions and Plant Development. Bklyn Bot. Gar. Mem., 1:119-122. (Original reference not seen.)

————. (1923) Minimum Light Requirements Referred to a Definite Standard. Bul. 235. Vermont Agricultural Experiment Station.

BUHLER (1922) Der Waldbau, Berlin.

CARBONNIER, HENRIK. (1933) Gallringsintervallets Inverkan På Produktionon Skogevårdsfören, Tidskr., 31:215-235.

CHEYNEY, E. G. (1932) The Roots of a Jack Pine Tree. Jour. Forestry, 30:929-932. Cloquet Forest Experiment Station. Unpublished Data.

CONRAD, J. P., and VEIHMEYER, F. J. (1929) Root Development and Soil Moisture. Cal. Sta.: Hilgardia, 4:113-134.

Craib, Ian J. (1929) Some Aspects of Soil Moisture in the Forest. Bul. 25, Yale School of Forestry.

Crocker, Douglas A. (1926) Pulpwood in the Lake States. American Paper and Pulp Assoc., Woodland Sections, Series No. 3.

Deen, J. Lee. (1933) Some Aspects of an Early Expression of Dominance in White Pine. Bul. 36, Yale School of Forestry.

Dengler, A. (1930) Waldbau auf Ökelogischer Grundlage. Julius Springer, Berlin.

Douglass, A. E. (1914) A Method of Estimating Rainfall by the Growth of Trees. The Climate Factor as Illustrated in Arid America. Carnegie Inst. Pub. 192.

Eide, Erling. (1926) Om Sommervarmens Innflydelse på Ärring bredden. Med. fra det Norske Skogforsøkevedsen, **7**:87-104.

Engler, A. (1904) Untersuchungen über das Wurzelwachstum der Holzarten. Mitteilungen der Schweiz. Centralanst. f. d. Forestl. Versuchsv: **7**:247-317.

Fernow, B. E. (1916) Suggestions as to Possibilities of Silviculture in America. Proc. Soc. Am. For., **11**:171-176.

Fricke, K. (1904) "Licht und Schattenholzarten" ein Wissenschaftliches nicht Bergründet Dogma., Centrallbladt f. d. Gesamte Forstwsn., **30**:286-305.

Friedrich, Josef. (1897) Über den Einfluss der Witterung auf dem Baumzuwachs. Mitt. Forstl. Versuchsw. Österr. 22.

Gerhardt, E. (1930) Zum Streit über die Zuwachsfordernde Wirkung von Starke-Durchforstung und Schnellwuchsbetrieb. Zeitschr. f. Forst. u. Jagdw. **62**: 281-301.

Gevorkiantz, S. R., and Zon, Rapheal. (1930) Second Growth White Pine in Wisconsin. Research Bul. 98, University of Wisconsin Agricultural Experiment Station.

Grasovsky, Amihud. (1929) Some Aspects of Light in the Forest. Bul. 23, Yale School of Forestry.

Gray, Asa. (1908) Manual of Botany 7th Edition. American Book Co., Chicago.

Guttman, Otto. (1925) Durforstungsversuche im Fichtenbestanden.

Hansen, H. C., and Brenke, B. (1926) Seasonal Development of Growth Layers in *Fraxinus campestris* and *Acer saccharinum*. Bot. Gaz., **82**:286-305.

Hansen, T. S., and Brown, R. M. (1929) Some Results of Thinning Jack Pine. Jour. Forestry, **27**:275-279.

Hansen, T. Schantz. (1931) Thinning 27-Year-Old Jack Pine. Jour. Forestry, **29**:544-550.

Harris, J. A., Kuenzel, J., and Cooper, W. S. (1929) A Comparison of the Physical Factors of Habitats. Jour. Ecology, **10**:47-66.

Hartig, R. (1891) Anatomie und Physiologie der Pflanzen. Berlin.

Hawley, R. C. (1922) Progress of the Results Secured in Treating Pure White Pine Stands. Bul. 1, Yale School of Forestry.

————. (1927) A Second Progress Report of the Results Secured in Treating Pure White Stands. Bul. 20, Yale School of Forestry.

————. (1935) The Practice of Silviculture. John Wiley and Sons, New York.

Heck, C. R. (1931) Handbuch der Freien Durchforstung. Stuttgart.

Hesselman, Henrik. (1904) Om Tallens Hojdtillväxt och Skottbildning Sommaren 1900-1903. Skogesvårdsför. Tidskr., **2**:79-95.

————. (1904) Om Tallens Diameter Tillväxt under de Siste Tio Aren. Skogesvårdsfor. Tidskr., **2**:489-496.

————. (1925) Studier over Barrskogens Humustäcka, Dens Egenskaper och Beroende ov Skogsvården. Medd. fr. Stats. Skogsforsöksanstalt, **22**: 169-552.

Hiley, W. E., and Cunliffe, Norman. (1922) An Investigation into the Relation Between Height Growth of Trees and Meteorological Conditions. Oxford Memoirs No. 1192. Review in Jour. Forestry, **20**:890-892.

Humphrey, R. R. (1933) A Detailed Study of Desert Rainfall. Jour. Ecology. **14**:31-34.

Jost, Dr. Ludwig. (1907) Lectures on Plant Physiology. Translated by R. J. Harvey Gibson, Clarendon Press, Oxford.

Kittredge, J. (1929) The Importance of Time and Rate of Change in Forest Soil Investigations. Reprint from the Proceeding of the International Congress of Forestry Experimental Stations, Stockholm, pp. 479-484.

Korstian, C. F. (1920) Effect of Thinning and Pruning Upon Diameter Growth of Western Yellow Pine. Jour. Forestry, **18**:304-305.

———— et al. (1921) A Chlorosis of Conifers Corrected by Spraying with Ferrous Sulphate. Jour. Agric. Research, **21**:153-171.

Kunze, M. F. (1918) Untersuchungen über den Einfluss Verschiedener Durforstungsgrade auf den Wachsetumsgang eines Kiefernbestandes. Mitt. aus den Sach. Forst Versuchsanstalt zu Thorandt. **1(2)**:55-84.

Laitakari, E. (1920) Untersuchungen über die Einwirkung der Witterungsverhältnisse auf den Langen und Dichenwachstum der Kiefer. Acta Forestalia Fennica. 17.

Lehenbauer, P. A. (1914) Growth of Maize Seedlings in Relation to Temperature. Physiol. Research, **1**:247-288.

Li, Tsi-Tung. (1926) Soil Temperature as Influenced by Forest Cover. Bul. 18, Yale School of Forestry.

Livingston, B. E. (1907) Evaporation and Plant Development. Plant World, **10**:269-276.

————. (1916) Physiological Temperature Indices for the Study of Plant Growth in Relation to Climatic Conditions. Physiol. Research, **1**:399-420.

Lodewick, J. E. (1930) Effect of Certain Climatic Factors on the Diameter Growth of Longleaf Pine in Western Florida. Jour. of Agric. Research, **4**: 349-363.

Lundegardh, H. (1925) Klima und Boden in ihrer Wirkung auf das Pflanzenleben. Jena.

Markwardt, L. J. (1930) Comparative Strength Properties of Woods Grown in the United States. U.S.D.A. Tech. Bul. 158.

Merriam, C. H. (1898) Life Zones and Crop Zones. U.S.D.A., Biol. Sur. Bul. 10.

Meyer, Walter H. (1930) Diameter Distribution Series in Even Aged Forest Stands. Bul. 28, Yale School of Forestry.

————. (1931) Thinning Experiments in Young Douglas fir. Jour. Agric. Research, **43**:537-546.

Mitchell, J. A., and Zon, Rapheal. (1929) Forest Fire Hazard. Research Bul. 91, Agricultural Experiment Station, University of Wisconsin.

————. (1930) Interception of Rainfall by the Forest. Jour. Forestry, **28**: 101-102.

Möller, C. M. (1931) Starke Durchforstung und Dänischer Beloeuchtung. Zeitscher f. Forst und Jadgw. **63**:369-395.

Öelkers. (1914) Jahrring und Licht Zeitscher, f. Forst und Jadgw. **46**:419-455.

PEARSON, G. A. (1918) The Relation Between Spring Precipitation and Height Growth of Western Yellow Pine Saplings in Arizona. Jour. Forestry, **16**: 677-689.

————. (1930) Light and Moisture in Forestry. Jour. Ecology, **11**:145-159.

————. (1931) Forest Types in the Southwest as Determined by Climate and Soil. U.S.D.A. Tech. Bul. 247.

PAUL, BENSON H. (1930) The Application of Silviculture in Controlling the Specific Gravity of Wood. U.S.D.A. Tech. Bul. 168.

————. (1932) The Relation of Certain Forest Conditions to the Quality and Value of Second Growth Loblolly Pine Lumber. Jour. Forestry, **30**: 4-21.

————. (1932) Improving the Quality of Second Growth Douglas Fir. Jour. Forestry, **30**:682-686.

————. (1933) Quality vs. Size as an Index of a Profitable Tree. Jour. Forestry, **30**:831-833.

ROBBINS, W. J. (1921) Precipitation and the Growth of Oaks at Columbia, Missouri. Research Bul. 44. Missouri Agricultural Experiment Station.

ROESER, J. J. (1932) Thinning Jack Pine in the Nebraska Sandhills. Jour. Forestry, **30**:918-924.

ROMELL, L. G., and HEIBERG, S. O. (1931) Types of Forest Humus Layers. Jour. Ecology, **12**:566-608.

SCHÄDELIN, DR. W. (1934) Die Durchforstung als Auslese und Veredslungsbetrieb Höchster Wertleistung. Verlag Paul Haupt, Bern-Leipzig.

SCHLICH, SIR WILLIAM. (1910) Manual of Forestry, Vol. II. Silviculture, 4th Edition.

Society of American Foresters' Committee on Terminology. Jour. Forestry, **15**: 68-101.

SCHOTTE, GUNNAR. (1912) Om Gallringsförsök. Skogsvårdsfören. Tidskr., **10**: 387-445.

SCHWAPPACH. (1904) Freien Durchforstung. C. R. Heck.

SCHWARZ, DR. FRANK. (1899) Reference in "Freien Durchforstung" C. R. Heck, Stuttgart.

SCHUBERT, J. (1931) Niederschlag und Kiefernwachstum. Zeitschr. f. Forst und Jagdw. **63**:638-642.

SHIRLEY, H. L. (1929) The Influence of Light Intensity and Quality upon the Growth of Plants. Amer. Jour. Botany, **16**:354-389.

————. (1932) Light Intensity in Relation to Plant Growth in a Virgin Norway Pine Forest. Jour. Agric. Research, **44**:227-244.

SHREVE, F. (1915) The Vegetation of a Desert Mountain Range as Conditioned by Climatic Factors. Carnegie Inst. Pub. 217.

STALFELT, M. C. (1924) Tallens och Granens Kolsyreassimilation och dess Ekologiska Betingelser. Meddel. Statens Skogförsöksanst, **21**:181-258.

STEER, HENRY B. (1931) Stumpage and Log Prices for the Calendar Year 1928. U.S.D.A. Statistical Bul. 32.

————. (1931) Stumpage and Log Prices for the Calendar Year 1929. U.S.D.A., Statistical Bul. 36.

————. (1932) Stumpage and Log Prices for the Calendar Year 1930. U.S.D.A. Statistical Bul. 37.

————. (1933) Stumpage and Log Prices for the Calendar Years 1931-1932. U.S.D.A. Statistical Bul. 44.

Sterret, William Dent. (1920) Jack Pine. U.S.D.A. Bul. 820.

Stevens, Clark Leavitt. (1931) Root Growth of White Pine. Bul. 32, Yale School of Forestry.

Sudworth, George B. (1897) Trees of the United States Important in Forestry. Reprint from U.S.D.A. Year Book 1897.

Toumey, James W., and Neethling, Ernest J. (1923) Some Effects of Cover over Coniferous Seed Beds in Southern New England. Bul. 9, Yale School of Forestry.

——— ———. (1924) Isolation a Factor in the Natural Regeneration of Certain Conifers. Bul. 11, Yale School of Forestry.

——— ———. (1928) Foundations of Silviculture. John Wiley and Sons, New York.

——— ——— and Kienholz, Raymond. (1931) Trenched Plots Under Forest Canopies. Bul. 30, Yale School of Forestry.

Wackerman, A. H. (1925) Yield Tables for Jack Pine. Unpublished M. S. Lake States Forest Experiment Station, U.S.F.S.

Wallace, H. A., and Snedecor, George W. (1931) Correlation and Machine Calculation. Official Publication Iowa State College of Agriculture and Mechanic Arts 23, No. 35.

Wallen, Axel. (1932) Till Kännedom om Klimatet i Skogen och andre Vegetationsomhällen. Skogvårdsför. Tidskr. **30**:374-401.

Weaver, J. E., and Clements, F. E. (1929) Plant Ecology. McGraw-Hill Book Co., Inc., New York.

Wiedemann, E. (1929) Starke Durchforstung und Schnellwuchsbetrieb. Zeithschr. f. Forst und Jadgw. **61**:701-721.

Wiesner, J. (1907) Der Lichtgenuss der Pflanzen. W. Engelmann. Leipzig.

Zon, R., and Graves, H. S. (1911) Light in Relation to Tree Growth. U.S.D.A. Forest Service Bul. 92.