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THE DEVELOPMENT OF SITE CONCEPTS AT THE HARVARD FOREST AND THEIR IMPACT UPON MANAGEMENT POLICY

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CONTENTS

TABLES

ABSTRACT

For half a century the Harvard Forest has applied intensive management to an area of woodland in central Massachusetts. In 1908, an attempt at sustained yield management, based largely upon the harvest and natural regeneration of white pine, was started. At this time, no tested methods of accomplishing this aim were available. However, European experience in forest management promised to serve as a guide, and could be applied to the considerable body of information concerning the natural history of native American trees.

Operating without endowment other than the growing trees, the Harvard Forest was required from the outset to take strict cognizance of the economics of forest production. Success of the management plan depended upon the regeneration of white pine; and the regeneration had to provide at least a modest return on the investment.

The first signs that natural regeneration of white pine might be difficult to achieve appeared within three years after the first experimental cuts had been made. Although problems of seeding and seed germination had been solved, young hardwoods of seedling and sprout origin threatened to overtop the young pines, and thus lead to their elimination from the new stands. This ominous development provided the impetus for research in many areas. Studies of the history of the pure stands of white pine led to the discovery that almost all pine stands growing on uplands had originated on abandoned plowland or open pasture. These historical studies also permitted a general reconstruction of the nature of the pre-Colonial forest and the history of land use in the area. Comparative studies of the growth rates of pine and species of hardwoods in the young volunteer stands that had followed the cutting of old field white pine stands showed the necessity for early and repeated removal of the hardwoods if the pines were to survive. These comparative studies also showed that relative rates of growth of pine and hardwood varied with differences in site, chiefly defined in terms of soil materials. This information promised to provide a means of reducing investment in cultural treatments, and resulted in changes in management policy.

In 1908, the aim of management was to reproduce the pure stands of white pine. By 1918 the aim was modified to the creation of mixed stands of pine and hardwoods. Continued difficulty with the regeneration of white pine, becoming more and more apparent as the number of regenera-

tion experiments increased and the results of the older experiments became clearer, led in 1925 to the goal of mixed stands of pine and hardwoods on specific sites defined in terms of soil.

Site recognition in terms of stand establishment, not production rates, thus assumed critical importance in white pine silviculture at the Harvard Forest. Site recognition offered a method of obtaining the most valuable tree species without an exorbitant investment in hardwood control. However, the knowledge of site components needed to predict the course of stand development was not then available. The philosophic frame had been erected, but site recognition depended heavily upon observation of the behavior of the trees themselves, and thus lacked prediction value. Nor did the first studies of the soil materials contribute much to the problem of site recognition. Rather, they attempted to show that the low quality of old field white pines and the difficulty in obtaining pine regeneration was the result of soil depletion under pure stands of pine.

In the 1930's most of the white pine regeneration experiments on the uplands were recognized as definite failures. White pine was virtually absent from the mixed hardwood stands, in spite of repeated cultural treatments. In 1935, a comprehensive plan for the management of hardwoods was presented, which required essentially the same kind of site evaluation as that proposed for the management of pine in 1925. In 1938 the remainder of the uncut old field white pine was destroyed by a tropical hurricane. The Harvard Forest then turned to the management of hardwoods and the coniferous plantations.

Beginning in the 1930's, research in forest history and in many aspects of environment expanded rapidly. Detailed studies of such things as past use of the land, microclimate, topographic form, and the nature and distribution of the glacial deposits and the soils, provided information essential to the solution of the long-standing problems of site recognition. The partial assimilation of this diverse material in terms of the distribution of tree species and forest types has already provided some basis for the prediction of stand development that is grounded in the characteristics of the sites themselves.

INTRODUCTION

In this period of increasing population pressures and international tension, the conservation of natural resources is a matter of grave concern to many individuals and agencies, both public and private. Our forested lands constitute a major part of our renewable natural resources, and our forest management techniques and policies are being subjected to an increasingly critical scrutiny.

Discussion of forest management among professional foresters generally turns toward more intensive management, often leading to a consideration of the careful nurture of trees as a crop in the agricultural sense. These management objectives imply varying degrees of control over the course of stand development. Control requires, among other things, a knowledge of the relations between forest stands and the habitats in which they grow. Thus, site evaluation or the classification of habitats on the basis of their ability to produce specific forest products at a known rate becomes increasingly important as management becomes intensified.

The main purpose of this paper is to point out, by means of an analysis of experience at the Harvard Forest, that site evaluation consists of two distinct phases that blend into one in those few places where intensive forest management has been carried through more than one rotation of the tree crop. The first phase consists of the classification of sites in terms of the probability that a tree species or group of species will become established and form a part of a new stand. The second phase requires the analysis of production rates of a tree species in existing stands growing on a range of sites.

In a sense, this rather arbitrary subdivision of site evaluation emphasizes the fact that stand management requires a marrying of biological and economic fact. In other words, management decisions, in practice, rest not entirely upon biological potential as determined by comparative studies of successful stands, but to a large extent upon an ability to define that level of biological achievement which is economically feasible to attain in the present or the foreseeable future. Thus, knowledge of possible results ranging from absolute failure of establishment to full realization of the biological potential, as well as the probability that a specific result will be obtained at a certain level of management intensity, is critical in making rational management decisions for a specific area.

However, I believe that the primary justification for a two-phase consideration of site evaluation is biological. Lack of knowledge of the field relations of trees, compounded by methods of site analysis that emphasize the quantitative differences in production rates in established stands, gives rise to costly and disappointing errors in forest management. As will be shown later, knowledge of production rates in existing stands can actually serve to confuse solution of the problems of stand establishment.

Much of our site evaluation work has been concerned with conifers, most of which originate solely from seed. Historical events, such as fire, wind, and past use of the land, are known to affect the distribution of conifers profoundly at a point in time. Thus, production potentials derived from study of a particular site that supports a stand of conifers may be meaningless, for all practical purposes, if the origin of the stand depended upon past events that are not included in the criteria used to characterize the site.

The Harvard Forest has had fifty years of experience in dealing with a difficult problem in site evaluation, and the present review is offered as a case history that illustrates a series of attempts, by no means always successful, to develop a system of site recognition.

A fiscal structure that required the Harvard Forest to be financially self-sufficient, combined with the nature of the timber market and an accident of local geography, forced the staff to undertake site evaluation studies soon after the Forest was established. In short, a general failure to regenerate white pine in cutover pine stands threatened the continued existence of the Forest. The problem was not the comparatively simple one of classifying areas according to their productivity for white pine. It was rather the selection of areas in which white pine could be regenerated at a reasonable cost. Bear in mind that regeneration at all costs on an experimental basis was not possible within the financial framework of the institution. Thus, although the Harvard Forest was an experimental forest, it was at the same time a sort of pilot plant in that the silvicultural practices were required to yield income for the operation of the Forest. Little income was left over for investment in the establishment of new stands. This experimental disadvantage acted to hold the staff to what might be thought of as more realistic — certainly more pragmatic — endeavors. As the years went by, sheer desperation perhaps was a major factor in bringing about experimental innovations in what might have been a rather conservative silvicultural operation.

The studies of site at the Harvard Forest are significant not only because they span most of the period of professional forestry in the United States and thus reflect changes in points of view that were rather general, but also because the time span itself is highly important. Site evaluation studies carried out at a point in time contain drawbacks inherent to any study in which space is substituted for time.

The series of site evaluation studies reviewed here is perhaps unique in the United States. It encompasses almost two rotations of the forest crop, and during most of this period the Harvard Forest was under the control of a single policy maker, Professor R. T. Fisher. For the most part, these studies were conducted as an integral part of the management of the Harvard Forest, not as extraneous pieces of pure research. As will be shown, the problems raised during the establishment of reproduction of the desired species on cutover lands gave way to knottier problems of maintaining this species composition until the sapling stage was reached, which in turn gave way to another set of problems as the canopies closed and, in the case of hardwoods, became two-storied.

Studies of site at the Harvard Forest fall into three different phases covering three different periods of time. Until about 1925 the collection of materials bearing upon site problems was largely a by-product of the analysis of the silvicultural experiments. During this period the belief that stand manipulations would bring about the desired end products was strong; and although it was recognized that certain site variants might modify management aims in a minor way, faith in the control of stand development was unshaken. Nor was it much doubted that these treatments could be carried out even within the fiscal structure of the Harvard Forest.

In the mid-1920's, control of the course of development of the regeneration that followed the cutting of pine woodlots became increasingly difficult. In many of the cutover pine stands, even the restricted goal of a mixed pine and hardwood second crop began to look doubtful of attainment, and the search for an explanation of this imminent failure of policy brought on the first detailed studies of soils at the Harvard Forest. During this period, from 1925 to about 1938, attention was directed to the organic layers of the soil materials, reflecting a strong preoccupation with nutritional problems in the old field woodlands. As a tool for evaluating sites, this series of studies proved futile.

Beginning in 1938, there was a strong revival of interest in the physical characteristics of the soil materials, and lines of research that had been opened up between 1908 and 1918 were reexamined in detail. Careful studies of surficial deposits were made from the point of view of the glacial geologist as well as the pedologist, the land-use history was studied in detail on the ground, and studies of the microclimate were made. As this trend in research developed, a tendency to separate the studies from forest management — at least initially — became apparent. These studies often resulted in fundamental contributions to the knowledge of environments at the Harvard Forest. Evaluation of these contributions in terms of forest management is as yet incomplete.

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THE INITIAL MANAGEMENT PROBLEM

Most of the land comprising the Harvard Forest was given to the University in 1907, and management of the Forest was begun in the fall of 1908 (Fisher, 1921). Lying almost entirely within the town of Petersham, in northern Worcester County, Massachusetts, the Harvard Forest initially consisted of three separate tracts of land totalling 2068 acres, 1175 of which were forested (Fisher, 1921).

An inventory of the forested land made in 1908 showed a total of 10.5 million board feet of merchantable timber, about 10 million feet of which was white pine. In addition to the white pine, the forest contained about thirty species of trees that attain sufficient size at maturity to have actual or potential value as timber (Jack, 1911). The conifers included red and pitch pine, red and black spruce, and hemlock. The more valuable hardwoods included sugar maple, white ash, chestnut, hickory, basswood, black cherry, and several kinds of oak and birch. According to Fisher (1921, p. 8), the chief species were white pine, chestnut, red oak, white ash, black cherry, and hemlock. The acreage was rather uniformly distributed among the young, middle-aged, and old-aged stands.

This was the forest resource initially available to Fisher. Presumably his only restriction as to its use within the broad frame of forest management was that the forest be managed so as to provide income sufficient to operate the establishment. This restriction is implicit in his statement that the Harvard Forest was to serve primarily as "a model forest from which a yield as nearly continuous as possible can be cut" (Fisher, 1910).

Income, in turn, depended upon the market structure. In 1908, the cutting of hardwood was "comparatively unprofitable" (Fisher, 1921, p. 11), although a flourishing boxboard industry created a good local market for white pine. Prices had been stable for some time. The management problem seemed to be reduced to a sustained yield management of white pine.

The first step in sustained yield management was the determination of the annual increment of white pine in the Forest. Stands of all age classes that contained more than 50 percent by volume were included in the initial calculations. By use of a yield table published by the New Hampshire Forest Commission in 1906, a rotation of 60 years was chosen, which "is old enough for a stand to bear seed, and not far from the point where the mean annual growth in volume culminates" (Fisher, 1921, p.

11). Summarizing the growing stock by area in three 20-year periods showed in which age classes the growing stock was deficient, and Fisher was able to plan operations so as to give a steady yield of white pine (pp. 11–12):

> Considering the total volume of the stand, and the surplus of volume in the third period, the theoretical allowable annual cut would have been about 335,000 board feet. On account of the lack of tried silvicultural methods, and the need of a reserve of sizable timber for future scientific purposes, it was decided to put the annual cut at the conservative figure of 250,000 board feet, or the annual increment of the pine-bearing lands of the Forest.

If sustained yield were to be realized, a fundamental problem would be the successful regeneration of the cutover stands, either by natural regeneration or by planting. And, if sustained yield were to be thought of largely in terms of white pine, white pine seedlings must constitute most of the regeneration, whether natural or artificial.

THE STATE OF AMERICAN FORESTRY IN 1908

In the United States professional forestry can be said to have had its first permanent practitioner in the person of B. E. Fernow, a trained Prussian forester who came to this country in 1876 (Winters, 1950). Prior to Fernow's arrival, many people of diverse interests had gathered a rather large body of information concerning the different kinds of native trees, including their distribution and characteristics, and their general field relations. A growing body of thoughtful people viewed the rapid removal of the pre-settlement forest with concern, and were beginning to think in terms of forest improvement. For example, G. B. Emerson proposed in 1846 a rather comprehensive system of cultural treatments for the second growth forests of Massachusetts, including such operations as pruning and thinning. He also advocated the planting of trees on waste lands. Early enthusiasts, particularly in New England, were carrying out simple manipulations of this sort on private holdings, and there was considerable interest in European forestry techniques.

Until the rise of professional American forestry after 1876, however, there was little consideration of silvicultural systems, or methods of cutting the timber crop in such a way as to promote the natural regeneration of harvested stands of trees. To most people, forestry meant the planting of trees. Budding young foresters seeking professional training in Europe picked up the idea of silvicultural systems, as well as the companion idea of matching the silvicultural system to the silvical characteristics of the different species. With the establishment of professional forestry schools in America late in the 1890's, these concepts and the rest of the framework of European forestry were widely disseminated.

Silvicultural Systems

Hough (1882) and Fernow (1887, 1891, 1895, 1899) outlined silvicultural systems in a general way for American forest managers, and Pinchot (1905) described them in considerable detail. In *The Woodlot*, Graves and Fisher (1903) applied these general systems of silviculture to the specific problem of managing the second growth woodlands of southern New England. Their recommendations fell into five categories:

1) improvement cuts in immature stands; 2) reproduction cuts designed to insure rapid regeneration of desirable species in dense stands; 3) pruning; 4) protection from fire and grazing animals; and 5) reforestation of waste lands.

Graves and Fisher's treatment of reproduction cuts is of particular interest in this review. They voiced concern that cutting methods currently used in small woodlots — clear-cuts or the removal "from time to time [of] trees for special uses without regard to the effect on those remaining" (p. 7) — had resulted in a reduction of "the proportion of valuable species in many localities" (p. 7). Noting that white pine trees are "often abundant in gaps and on the edges of woods" (p. 17), they concluded that "this indicates that clearings must be made for good reproduction of White Pine" (p. 17). They therefore recommended four kinds of modified clear-cutting methods for the regeneration of white pine, certain kinds of hardwood stands, and other types of stands "where the seed of the desired species can not germinate or the seedlings live under the shade of the older trees" (p. 17): 1) the "scattered seed tree method"; 2) the "method of reserves" or the retention of clusters of seed trees or mixed seed trees and trees of other species; 3) the "strip method"; and 4) the "patch method". Cognizant that pine seeds do not germinate well "on a dry matting of needles and leaves" (p. 18), they recommended that the litter be burned; or better yet, mixed with the mineral soil. For the regeneration of most hardwood stands, Graves and Fisher recommended the use of the "selection method", or removal of single trees, the "sprout or coppice method", or the "method of selective thinning".

Improvement cuts and thinnings were recommended for immature stands, both hardwood, mixed hardwood and softwood, and softwood. Young pine seedlings should be assisted "by cutting away any poor specimens of hardwoods which are injuring them. In this way the Pines can be helped to start; later they will take care of themselves" (p. 18).

Prior to the publication of Graves and Fisher's report on the management of New England woodlots, Spalding (1899) had completed a monographic study of the white pine. He noted that pine of the highest quality was derived from mixed forests of white pine and hardwoods, although the highest yields came not from the mixed stands — which contained the largest trees — but from pure stands of pine. These observations, fortified by the experience of European forest managers, led him to conclude (p. 61) that "mixed growth is in every respect superior to pure growth; it will therefore be proper policy to grow White Pine preferably, if not altogether, in mixture with other species". In general terms, Spalding (p. 61) stated a method of regeneration for white pine:

> Unfortunately, our irrational exploitation has reduced the White Pine in the natural forest areas often to such an extent that its reestablishment is possible only by artificial means. Wherever the culling has not been too severe, and either young growth has developed or seedling trees have been left, the natural reproduction should be encouraged by favoring the young growth and by removing or thinning out other species which interfere with the starting of a young growth.

He closed a discussion of natural regeneration of white pine as follows (p. 63):

> White Pine reproduces well, seeds abundantly, and is so particularly well suited to natural reproduction that the most experienced and competent recent writers claim that this tree fairly "demands" this form of regeneration.

Spring's study of white pine stands in New England led him to believe that "the replacement of white pine can be assured by leaving seed trees on each lot when it is cut" (1905, p. 6). He recommended clear-cutting of the pine woodlots, leaving three or four seed trees scattered or grouped in each acre. For the larger woodlots, he proposed clear-cut strips located at right angles to the winds prevailing during seeding time. Spring also emphasized the benefits to be gained by cutting in good seed years.

A study of the forests of southern New Hampshire by Lyford and Margolin (1906) presented still another set of silvicultural recommendations, which, like the ones of Graves and Fisher, were rather detailed. Recognizing white pine as the most valuable tree in southern New Hampshire, Lyford and Margolin discussed silvicultural methods largely in terms of white pine stands. They concluded (p. 187) that "white pine may be grown to best advantage in pure, even-aged stands under a clear cutting system of management". To accomplish this goal, they recommended thinnings beginning at an age of 30 years in existing even-aged stands; pruning, if high quality was the aim; and clear-cutting at the end of the rotation. They tentatively recommended planting the cut-over areas with white pine the spring following the final cut, but offered as an alternative the system of clear-cutting in a seed year, leaving three seed trees per acre. They also offered the idea of clear-cutting in strips.

In pure, uneven-aged white pine stands, mixed white pine and gray birch stands, and partially stocked stands arising on abandoned farmland, they recommended in addition preliminary thinning, improvement cuts, and hole-filling by planting when feasible. Recommendations for the management of mixed pine and hardwood stands were rather general. They recommended improvement cuts based upon "desirability" of the hardwood species and the "relative tolerance of shade" possessed by the various species. The final or reproduction cut must recognize the fact that conifers do not sprout, and must be adjusted to the fact that the different kinds of hardwoods possess different sprouting characteristics.

Lyford and Margolin (p. 186) observed that pine seed required moisture for germination and that the growing roots must soon reach mineral soil:

> For this reason reproduction from seed cannot be secured where the soil is fully exposed to the drying action of the sun or where the litter of leaves and other vegetable matter is sufficient to prevent the roots of the seedling from reaching mineral soil.

Graves and Fisher's, Spring's, and Lyford and Margolin's reports represent attempts to apply European silvicultural techniques to the specific problem of managing the woodlands of central and southern New England. These papers were preceded by Spalding's study of white pine throughout its range, made from the particular point of view of professional forestry. Graves and Fisher, Spring, and Lyford and Margolin were concerned primarily with a problem basic to silviculture, the reproduction of forest stands. This concern was also an important part of Spalding's monographic study. It should be emphasized that their silvicultural recommendations depended almost entirely upon deductions from observations made in the forests at a point in time. In other words, applications of silvicultural systems derived from centuries of experience in Europe were made by deductive processes from silvical observations made in American forests. This procedure introduced a possible source of error which was fully recognized at the time. For example, Spalding (p. 61) wrote:

> As regards forest management, we have, unfortunately, in this country no experiences which would permit us to form very positive opinions based on actual observation regarding this species [white pine] or any other. The study of the natural history of the species in its native occurrence permits us, nevertheless, to draw conclusions which may at least serve as a basis for its future sylvicultural treatment.

Similarly, Lyford and Margolin (p. 185) wrote:

> In applying the methods suggested below it should be remembered that forest management in the region has yet to pass through the experimental stage, and that, therefore, all methods are more or less dependent on future experience.

Silvical Knowledge

Because the correct application of silvicultural methods depends upon a thorough knowledge of the silvics * of the various species, perhaps it would be of value to consider at this point the state of this branch of forestry in the United States in 1908, particularly that concerning white pine.

By 1900, a mass of information was available concerning the white pine. It was recognized as a valuable timber tree during the seventeenth century, was first described botanically in 1696, and was cultivated in Europe by 1705 (Sargent, 1897, p. 20). In New England the white pine has always been thought of as "the tree", capable of stirring deep emotion. In Sargent's words (p. 21):

> The most beautiful Pine-tree of eastern America, our sylvan scenery owes the peculiar charm which distinguishes it from that of all other parts of the world to the wide-spreading dark green crowns of the White Pine, raised on stately shafts high above the level of the forest roof and breaking the monotony of its sky-line.

The great value of its wood did not detract from this feeling. According to Spalding (p. 11), the abundance of white pine "and the combination of qualities which adapts it to an almost unlimited number of uses have made it the most important and the most highly prized of all the timber trees of the region to which it is indigenous".

Although the properties and uses of the wood of white pine, the form and structure of its shoot and root, its geographic range, its general characteristics under cultivation in the nursery and to some extent in plantations, and its general growth characteristics under a variety of circumstances in nature were well known by 1900, many of its physiological requirements, particularly those involving its field relations in different kinds of environments and in mixed stands, were less well understood. Unfortunately, knowledge of these latter characteristics was essential to foresters confronting the problems of managing natural stands containing white pine. Furthermore, if the origin of existing natural stands was to be understood, and their successful regeneration under management realized, knowledge of the natural history of white pine would be needed for the whole life span of the tree. Many of the components of this knowledge were already available in the literature, but they were scattered,

* Silvics is the study of what might be called the natural history of the different tree species — such things as their growth and form characteristics, life cycles, physiological requirements, and relations to environment.

fragmentary, and largely undigested. To add further to the confusion, not only were similar observations of fact interpreted in dissimilar ways, but the wide range of the species, covering a diversity of environments, inevitably created a wide variety of conclusions as to its field relations — many of which were perfectly valid within a particular region.

Seed Source

All systems of cutting designed to insure natural regeneration of white pine paid particular attention to the provision of a source of pine seed. Spalding (p. 23) reported that "a full crop of seeds is usually produced by the same tree only at intervals of several years". A "seed year" resulted when a large number of pine trees in an area produced full crops of seed simultaneously. Seed years were reported as occurring at intervals of three to five years in Pennsylvania (Pinchot and Graves), five to seven years in New England (Spring), and three to seven years in southern New Hampshire (Lyford and Margolin).

From 10 to 20 percent of fresh seed will not germinate; and animals, fire, and destruction from excessive moisture or excessive drought results in the loss of "a very considerable part of the crop during the best seed years" (Spring, pp. 8–9). A deep layer of leaf and needle litter provides a poor seedbed (Graves and Fisher, Lyford and Margolin, and Spring), presumably because the young roots are unable to reach mineral soil (Lyford and Margolin, Spring). Seeds that fall in open areas mantled with "a cover of grass, weeds, moss, or ferns" obtain "favorable conditions of moisture" for germination (Spring, p. 9).

According to Spalding (p. 62), in York County, Maine:

> Repeated observations . . . led further to the conclusion that no dependence can be placed upon the springing up of seeds that have lain dormant in the ground for a term of years; or, in other words, although the seeds of the White Pine retain their vitality for a long time if kept in a dry place, there is a lack of evidence to show that this is the case in the natural forest, where they are alternately dry and wet.

Spring (p. 9) also emphasized the short life of pine seed in nature:

> The vitality of the seeds, their ability to take up moisture and germinate, grows less with age, and only a very small proportion ever germinate after the second spring following their ripening.

Growth of Seedlings

Spalding (p. 27) reported that the height growth of the pine seedling "is variable, according to the conditions under which it grows". Nevertheless, in the nursery, in open fields, and in the forest, he found uniformly slow growth during the first five years, generally less than a total height growth of 1 foot. He concluded (p. 28) from measurements of seedlings growing in forests:

> These measurements show that the rapid height growth begins with the sixth year, when the total growth of the first five years is almost doubled in one season. This, to be sure, holds only for seedlings favorably situated. In those less favored the rapid stage of development comes more gradually.

Spring (p. 10) measured 1600 white pine seedlings that were growing on open ground, and reported an average total height of 11 inches at five years, increasing rapidly to an average total height of 64 inches at ten years. He believed that "fire, frost, drought, and a deficiency of light" are especially dangerous to a seedling "during the first two years of its life".

Survival of Seedlings in Stands

In attempting to explain the success or failure of white pine seedlings to survive in pure or mixed stands, observers almost invariably resorted to theoretical discussions of so-called light requirements, both of the pine and its hardwood associates. This can be illustrated by a quotation from Spalding (pp. 30–31):

> According to the relative amount of light at the disposal of the crown the rate of growth differs, and there is found, therefore, in forest trees, though very nearly the same age, trees of different heights, according to the success of the struggle for light which they have had with their neighbors. . . . Thus a natural growth may start with a hundred thousand seedlings per acre; by the twentieth year these will have been reduced by death to 6,000, and by the hundredth year hardly 300 may be left, the rest having succumbed under the shade of the survivors.

White pine generally grew in mixture with other kinds of trees in the pre-settlement forests (Pinchot and Graves, Spalding, Spring), and the individual trees of highest quality were confined to mixed stands of pine and hardwood (Spalding). These facts constituted *prima facie* evidence of the ability of white pine seedlings to survive and reach a magnificent state of maturity in association with hardwoods. Everyone knew that trees require light if they are to grow; and if they grow in nature to great size, they obviously have received light in generous amounts. From this point it is but a short step in the deductive process to postulate that needleleaved trees growing in mixture with broadleaved trees must endure a considerable amount of shade, and to conclude that white pine is "shade tolerant".

Related to the ideas of shade tolerance, but probably more closely rooted in nursery experience, was the concept of the importance of shade for seedling survival. Sargent (1897, ftn. p. 21) stated that white pine "succeeds itself on land which has not suffered from fire if sufficient shade is left to protect the young and tender seedlings". Spring observed that cutover and burned pine lands in New England often became covered with a growth of gray birch, but "if seed trees are left near the tract, after some years the pine begins to come in under the birch, since the latter, when not too thick, affords a desirable shelter for the pine" (p. 18).

The shade tolerance of white pine was discussed in a general way by Spalding (p. 43):

> The capacity of the White Pine to keep its place in mixture with the hardwoods is probably mainly due to its shade endurance. In this respect it excels all pines with which we are acquainted. Pines are, as a rule, rather light-needing species, and are usually at a disadvantage in the mixed forest, unless compensating influences are in their favor. The White Pine is an exception. As a consequence, it is capable of forming dense thickets, supporting a larger number of trees per acre and producing a larger amount of material than the more light-needing species.

However, Spalding's field observations indicated that the idea of shade tolerance became complicated when applied to mixed stands (p. 43):

> As this shade endurance [of white pine] is, however, only relative, and as many of the associates possess it in greater degree, the additional advantage of rapid height growth alone saves the pine from being after all suppressed by its shadier companions. Yet, these succeed in keeping the young progeny of the pine subdued, and hence the observation that in the dense virgin forest of hardwoods the reproduction of White Pine is scanty. . . .
>
> Its shade endurance is decidedly less than that of the Spruce, which maintains itself, but not thriving under the dense shade of Maple, Birch, and Beech, where White Pine seedlings and saplings are not to be found, although they sustain perfectly the shade of oaks. To be sure, this shade endurance is to some extent dependent on moisture conditions of soil, being less on the drier than on the fresher soils.

Thus Spalding believed that the superior shade-endurance of maple, birch, and beech — but not oak — could prevent the survival of white pine to the period of rapid growth when the pine could outgrow its associates. These ideas of shade tolerance he then applied to the problem of pine regeneration (p. 43):

This relatively high shade endurance permits ready natural reproduction of the pine, especially where the hardwoods have been thinned out to some extent, or where, after clearing, all species start their race for reoccupation of the soil with equal chance. The pine then appears in the young hardwood growth in single individuals at first, somewhat behind in height, but finally, when it enters upon the period of rapid height growth, it outgrows its competitors and is assured of its place.

Spring (p. 11) organized a series of observations concerning white pine into an even more comprehensive discussion of light requirements:

Sunlight is not essential to seed germination, yet it is required as soon as the first needlelike leaves appear on the young stem of the seedling. Seeds often germinate in places where little light enters, but eventually they will die for lack of it. Pines which come up under pine woods in fairly dense shade often live for several years, though spindling and stunted. In open, young stands, white pine seedlings are more vigorous and may, under favorable conditions, live to form a component part of the mature stand. Pines which start in the open field or pasture have a sturdy growth, are often bushy in appearance, and are quite different from the slender seedlings found in the woods. This character of development shows the light requirements of the white pine. . . . In a scale of tolerance — that is, the ability to endure shade — it occupies an intermediate position between trees like the hemlock, which can grow in fairly deep shade, and those like the gray birch, which requires full sunlight from the beginning of its life.

He combined the ideas of seed years, tolerance, and rapid subsequent growth of pine seedlings to arrive at a hopeful picture of white pine regeneration on cutover, but unburned, pine lands (pp. 18–19):

Land which is not burned over after being lumbered furnishes a better opportunity for the replacement of pine by the same species. . . . Under favorable conditions a good stand of pine results at once, but if a seed year does not occur until five or six years after the lumbering, the pine has to contend with the growth of birches and other species which will have sprung up in advance. This stand of birch, however, is likely to be less dense than a stand on the burned land, and the rapid height growth of the pine after its fifth year usually gives it a good chance to push up through the light foliage of the other species and to establish itself as the predominant tree.

The varying numbers of pine seedlings to be observed in existing stands was further explained by Spring (pp. 19–20), again largely in terms of relative degrees of shade tolerance:

Another phase of pine reproduction is that of seedling stands in rather open woods. Moisture conditions as well as shelter are favorable to repro-

> duction, but the seedlings grow much more slowly than those in open pastures. One condition which is quite common is the reproduction of white pine under pitch pine on very loose, sandy soil. The pitch pines are usually well separated, the canopy thin, and the ground in good condition for seed germination. Under these trees a perfect thicket of white pines frequently exists.
>
> Stands of hardwoods sometimes offer a favorable opportunity for pine growth but they are usually too dense to allow many of the pines to survive.
>
> Seedling white pines under older trees of the same species do not thrive unless the stand is a very open one, a condition not often found.

According to Pinchot and Graves (p. 18), white pine seedlings in Pennsylvania "bear a good deal of shade provided they have germinated and grown under the cover of older trees". They observed pine seedlings growing under "the cover of dense Pine and Hemlock woods, [that] were alive and struggling even among the mountain Laurel". They concluded (p. 18) that "where some side light reaches the plants, they withstand a large amount of shade from above".

Graves and Fisher believed that the shade tolerance of white pine would allow its survival in at least some hardwood mixtures, but advocated a mild sort of weeding operation for an unstated but presumably short period of time (p. 18):

> In applying these [cutting] methods to Pine, hardwoods will often spring up on the cleared areas. If, however, the seed trees are at hand, Pine seedlings quickly follow, coming up under or with the hardwoods. They will survive under a low cover of hardwoods having light foliage, such as Oak and Birch. The woodsman should then look out for the young Pine seedlings and assist their growth by cutting away any poor specimens of hardwoods which are injuring them. In this way the Pines can be helped to start; later they will take care of themselves.

Although several writers reported height growth of pine over a period of years, most ceased to concern themselves with height growth in terms of saplings and older trees, emphasizing the onset of rapid height growth beginning with the sixth year. Not one of the papers reviewed here made comparative studies of height growth over time of pine seedlings, hardwood seedlings and hardwood sprouts. Nevertheless, Pinchot and Graves made observations that indicated the possible failure of white pine regeneration in cutover areas because of hardwood sprouts. They noted (p. 18) that young white pine seedlings

> which have started in the open . . . are easily overgrown and killed by

> hardwood sprouts and fast-growing hardwoods from the seed. Many seedlings of White Pine were found suppressed at the age of about twelve to fifteen years.

"Open" is assumed to mean "cutover" because of the reference to sprouts and because of the following sentence in the same paragraph: "In open spots, along roadsides, and in old pastures and deserted fields, young growth is very common".

Concerning the shade tolerance of white pine, Lyford and Margolin stated (p. 185):

> White pine is only moderately tolerant of shade. During the first few years of their existence the seedlings are less exacting, but their further development is dependent on a fairly abundant supply of light.

Although they discussed the problem of hardwood sprouts in several places, in their discussion of the post-settlement changes in the forests of southern New Hampshire they concluded, unlike Pinchot and Graves, that white pine could outgrow even the hardwood sprouts (p. 174):

> This clearing of the [pre-settlement] forests, supplemented by fire, was followed by an even-aged second-growth, the composition of which was largely determined by the relative abilities of the various species to reproduce under the conditions thus brought about. The hardwoods, which all sprout from the stump, were given an advantage over the softwoods, which do not sprout. White pine, although further handicapped by the infrequency of its seed years, escaped serious depletion by virtue of its rapid and vigorous growth.

Forest Succession

In spite of the optimistic assertions by most of the early foresters that white pine seedlings would survive in cutover areas, even in mixture with hardwoods, many observations of forest successions had been reported that involved a shift in composition from predominantly pine to predominantly hardwood, particularly after a cutting operation. Many of these observations were dismissed as indicating a lack of seed for white pine regeneration. Grounds for this belief existed in the fact that hardwood stands were known to have been succeeded by pine stands, as well as pine stands succeeded by pine stands.

Hough (1878, pp. 190–193) reviewed the reports of forest successions, or "alternations in timber-growth", in America. As early as 1814 the succession of oak by pine, and the reverse, had been observed in the southern United States. Among the more than a dozen examples of forest succession cited by Hough was one that involved Bristol County, Massachusetts, where "in some cases after pines have been cut off, oak, maple, and birch have sprung up abundantly" (p. 191). Reviewing a paper published in 1865 * Hough wrote (p. 192):

> Mr. Winslow C. Watson, of Port Kent, N. Y., notices the changes of character in forests — pines being almost uniformly succeeded by a deciduous wood, and the second growth on the site of a hard-wood forest being as often followed by evergreens and soft-wood trees. He considers the instances as rare and exceptional, in which the primitive forest is succeeded by the same genera of trees. The most careful observation could fix no rules that control these operations of nature.

Hough acknowledged that climatic changes might cause forest successions, and suggested that "the aggressive tendencies of other trees may result from the exceptionally fine conditions of the places where their seed may chance to fall" (p. 192).

G. B. Emerson (pp. 19–30) reported several instances of forest succession in Massachusetts and, comparing them to crop rotations, looked upon them with favor (p. 19):

> Nature points out, in various ways, and the observation of practical men has almost universally confirmed, the conclusion to which the philosophical botanist has come from theoretical considerations, that a rotation of crops is as important in the forests as it is in cultivated fields. A pine forest is often, without the agency of man, succeeded by an oak forest, where there were a few oaks previously scattered through the wood, to furnish seed. An oak forest is succeeded by one of pine, under the same conditions. But it frequently happens that there are not enough trees of the opposite family to seed the ground: in which case a forest will be succeeded by another of the same kind, which, though it will grow, will probably not flourish with the same luxuriance as would one of another family.

Emerson believed that a stand of trees often exhausted the supply of nutrients required by its constituent species, and must therefore be succeeded by other species having different nutritional requirements. As evidence he cited several concrete examples of succession (pp. 29–30):

> . . . Mr. Metcalfe, of Lenox, says, — "A forest of beech and maple is now growing on my father's farm, where stumps of white pine and some of oak and chestnut, are very numerous and very large." Oaks and pines most frequently succeed each other. Mr. E. Swift, of Falmouth, writes, — "Many

* W. C. Watson. Forests: their influences, uses, and reproduction. Transactions of New York State Agricultural Society.

instances have occurred in this town, of pine lands having been cleared of the pine timber, which has been succeeded by a spontaneous growth of oak." J. H. Cobb, Esq., of Dedham, says, — "I have known pine succeeded by hard wood in several instances." Mr. S. Freeman, of Brewster, declares, — "I have known frequent instances, where a forest of oaks has been entirely cut down, and succeeded by a growth of pine, and vice versa." . . .

This alternation is not, however, universal. In order that it should take place, the woods must contain trees of various kinds sufficient to supply the whole surface with seed. When this is the case, a wood of one kind will usually be found full of little trees of other kinds. "Upon clearing off the old growth, the undergrowth, which has been kept from the sun, shoots up with astonishing rapidity."

Apparently the white pine — hardwood succession was well known to loggers and sawmill operators in New England. Thus C. A. M., of Epping, Rockingham County, New Hampshire stated (Egleston, 1884, p. 366): "Pine lands when cleared grow up to other kinds; often to birch or maple. Pasture lands grow up to pine."

Pinchot and Graves observed forest successions in Pennsylvania, and visualized them as cyclical. However, they offered no explanation for the process (p. 17):

Upon better soils, where hardwoods were formerly mixed with the Pine, they take its place, at least for a time. The indications are very strong that the Pine, if left to itself, will at length resume possession of practically all the situations it occupied in the virgin forest.

They postulated other kinds of succession based upon different degrees of shade tolerance, which could be upset by natural catastrophe (pp. 23–24):

It is easy to see how the Hemlock, in these old forests, might gradually replace the Pine through the operation of its wonderful capacity to endure shade. There are comparatively few Pine seedlings in such dense groups, whereas young Hemlock occurs in abundance. After the old Pine veterans die off it seems likely that the Hemlock will remain. In all probability the many pure or nearly pure Hemlock groups in these mountains originated through the survival by the Hemlock of one species after another, because of its great shade-bearing powers. That bodies of Pine occur on land which the Hemlock would tend to occupy to its exclusion is often to be explained by the fact that, although it may once have been driven out, the Pine has returned in the windfall clearing made by a storm. The same results would follow a devastating fire. Such accidents exert an undoubted influence on the mixture and topographic distribution of species.

Elsewhere, Pinchot (1899, p. 39) suggested that variations in the method of seed dissemination provided a possible explanation for successions:

> Such facts [methods of seed dispersal and germination requirements] help to explain why, in certain places, it happens that when Pines are cut down Oaks succeed them, or when Oaks are removed Pines occupy the ground. It is very often true that young trees of one kind are already growing unnoticed beneath old trees of another, and so are ready to replace them whenever the upper story is cut away.

After studying pine areas in Maine and Michigan, Spalding concluded (pp. 62–63) that "practically everything depends upon reseeding", hardwoods following pine when pine seed is not available:

> All observations reenforced the truth that there is no mysterious succession of forest growth, involving necessary alternations, and that the White Pine does actually grow and flourish for an indefinite number of generations on the same land, if only the necessary seeding has been insured.

Graves and Fisher (p. 7), like Pinchot and Spalding, attributed pine — hardwood successions largely to the seeding processes:

> It is well known that when White Pine is cut, hardwood frequently forms the next growth. This happens when neighboring hardwoods have seeded up the ground under the old pines where pine seedlings could not start on account of the shade. If the hardwoods have not seeded up the ground, a new growth of pine follows the old pine, provided there are trees near at hand to furnish the seed.

Spring believed (p. 21) that the failure of white pine to reproduce in dense shade plus the sprouting capacity of hardwoods explained the shift from mixed forests of white pine and hardwoods to hardwoods in southern New Hampshire:

> Wherever the pine alone was cut, the remaining hardwoods secured full possession of the soil, owing to the inability of pine to reproduce itself in dense shade. Sprout hardwoods replaced the original hardwoods when they in turn were lumbered.

Thoreau (1861) offered a simple explanation for the succession of pine by hardwoods in New England, but little notice seems to have been taken of it. Close observation in stands of pine had revealed to Thoreau the presence of small hardwood seedlings. He attributed these seedlings to the annual planting of seeds by wind, squirrels, birds, and other animals. He noted that the denser the pine stand, the more the likelihood of hardwood seedlings, because "the planters incline to resort with their forage to the closest covert" (pp. 13–14).

Field Relations of White Pine

The distribution of tree species in the pre-settlement and the second growth forests often were described in terms of topographic variation and, particularly, in terms of soil characteristics. Nevertheless, this kind of evidence of site requirements seldom was incorporated to any extent in the silvicultural recommendations of the early foresters. Perhaps this omission was the result of a concept of management that aimed toward the reproduction of stands, not toward drastic conversions. Barring soil exhaustion, it would be logical to assume that an area that supported a certain group of species would support a similar group of species after the existing stand was cut, particularly if the method of harvesting was designed primarily for this purpose. Furthermore, the ability of white pine to occupy abandoned farmland in numbers sufficient to form pure stands on almost any kind of site confused and obscured the importance of site considerations.

Site considerations were largely in the realm of rates of growth by species, although many valuable observations concerning the germination and survival of seedlings in terms of site were made.

G. B. Emerson (p. 56) described the soil materials that generally supported white pine, and recognized a relationship between the local distribution of other conifers and moisture regimes:

> The soil natural to most of the pines is a sand formed originally by the crumbling or disintegration of the granitic rocks. These, in the forms of gneiss, mica slate and granite, are the prevailing rocks of Massachusetts; large portions of which, moreover, are overspread by the diluvium of sand formed from them. A large part of the surface was, therefore, and in many places still is, covered with forests of pine. The different species are adapted to the opposite extremes of moisture and dryness. The pitch pine flourishes on arid and parched sands; the white cedar thrives in swamps which are inundated almost through the year; the white pine prefers a situation moderately dry, but is often found in swamps; the red cedar and larch are found on rocky hills nearly destitute of soil, and the spruce and hemlock grow naturally in places inclined to moisture.

He noted a further relation between soil materials and high quality white pine (p. 63): "It [white pine] occurs in every part of New England; growing in every variety of soil, but flourishing best in deep, moist soil of loamy sand."

Hough (1882, p. 320) described the optimum white pine site in terms of topography and soils: "The white pine thrives best in a light sand, with a clay subsoil, and it prefers plains and broad river valleys to higher lands. It can scarcely be made to grow upon a limestone soil. . ."

Pinchot and Graves' reconstruction of the general distribution of white pine in the pre-settlement forests of Pennsylvania (pp. 14–17) is a careful description of variation in species composition in relation to topographic form and slope orientation. They stated (pp. 16–17), however, that white pine grew on almost all kinds of soil materials:

> In general, White Pine thrives on a great variety of soils. It is found on the poorest, driest sand, on steep, rocky slopes, on the rich vegetable earth of hollows and ravines, and again on moist clay flats and river bottoms. A strip of second-growth Pine frequently occurs on the brow of a hill from which old timber has been removed. Similar bodies are often found near the tops of slopes, sometimes on very poor soil.

Sargent (1897, p. 19 and ftn. pp. 19–20) discussed the distribution of white pine, noting the relationship between pure stands and soil materials, and the characteristics of the site producing wood of the highest quality:

> Sometimes on sandy drift it forms nearly pure forests, but more often it is found in groves, a few acres in extent, scattered through the forests of deciduous-leaved trees, on fertile well-drained soil, where its roots can reach abundant and constant moisture. Less commonly it grows on slight elevations and ridges surrounded by swamps, or along their borders and the banks of streams, on river flats overflowed during part of the year, and occasionally in swamps, where it does not reach a large size or produce valuable timber.
>
> The so-called pumpkin pine is the close-grained satiny and very valuable wood of large trees which have grown to a great age in rich, well-drained soil and have been favored with abundant air. Such trees are usually scattered singly through forests of deciduous-leaved trees, and are nowhere abundant.

Spalding's monograph of white pine is a rich source of information concerning the field relations of white pine, much of it quite involved and somewhat conflicting. Thus, in a general discussion of the relations between white pine, its associated species, and soil materials, he states (p. 40):

> While adapting itself readily to almost any variety of soil, the White Pine manifestly prefers one with a fair admixture of sand, insuring a moderately rapid drainage. The pine tribe in general occupies the sandy soils, to which it is better adapted than most of the deciduous tree species; but the White

Pine is capable of disputing possession with its competitors even of the fresh medium-heavy loam and clay soils, making here the best individual growth.

. . . Its growth on the rocky hills of Massachusetts within the hardwoods of that region is, however, at least for the first sixty to eighty years not much less thrifty than in the better soils in the valleys. It does not shun even the wetter and occasionally overflowed and swampy ground, and is here found, together with the Fir, Arborvitae, and even Tamarack; yet, on the dry, light sandy, coarse, and gravelly soil the Red Pine and Jack Pine seem to be able to outdo it. . . .

. . . Although it occurs in pure growths as true pinery on the red clays and moister gravels, it more frequently is an admixture in the hardwoods, sharing with them the compacter, heavier soils from which the other pines are excluded. . . .

. . . and there is hardly any species of the Northern Atlantic Forest which in one or the other region of its distribution may not be found in association with the White Pine.

Owing to the fact that the hardwoods as a rule occupy the better soils, the best individual development of the White Pine is also found in these mixtures.

This complex mixture of observation and conclusion is clarified by a series of descriptions of the field relations of white pine in different parts of its range (Spalding, pp. 12–16). For Michigan and Wisconsin, for example, Spalding presented (p. 14) a detailed description of the local distribution of white pine:

In Michigan the distribution of the species is entirely controlled by the character of the soil, all sandy areas being pinery proper, with large areas of pure growth of several square miles in extent containing only White Pine. Occasionally, and especially on the driest and poorest sandy gravels, the Red Pine associates and sometimes predominates. . . .

The typical pine forest on fresh sandy soils consists of White Pine (45 to 55 per cent of the dominant growth) mixed with Red Pine (25 to 45 per cent) with scattering Hemlock (10 to 15 per cent) and occasional Fir and hardwoods. The undergrowth, usually moderately dense, consists mainly of small Hemlock, Fir, and young hardwoods.

On moister sand with loam or clay subsoil Hemlock and hardwoods replace the pines, the Red Pine vanishing entirely and the White Pine occurring only in large isolated individuals. Into wet or swampy places the White Pine also penetrates in single individuals among Arborvitae, Hackmatack, and Spruce.

As the loam in the composition of the soil increases, the hardwoods increase numerically, the White Pine occurring only in single individuals and groups, and Red Pine and Hemlock only occasionally. Finally, the heavy clay soils toward the southern range of the species give absolute preponderance or exclusive possession to the hardwoods, mainly Sugar Maple, Yellow Birch, and Beech, although occasionally White Pine appears scattered, or even in smaller or larger groups.

> . . . Reproduction is satisfactory on the sandy areas wherever fires are kept out, which is rare; on the clay-loam areas reproduction under the shade of the hardwoods is practically impossible.
>
> In Wisconsin the same dependence on soil conditions in the distribution of the species prevails as in Michigan . . . the distribution is to the largest extent dependent on soil conditions, the sandy soils representing the pinery areas, in which merchantable hardwoods and Hemlocks are wanting; the loam and clay areas are stocked with the hardwood forest, in which both Hemlock and Pine occur scattering or in isolated groves, represented almost entirely by mature old timber. Saplings, bushy young trees, and seedlings are comparatively scarce, an active reproduction of the pine evidently not going on. This condition is found especially on the heaviest soils, where the hardwoods crowd out the pine, while on the sandy or gravelly soils the pine holds its own and forms a fair proportion of the sapling timber. In the true pinery of the sandy soils the hardwoods are scantily represented by small White Birch, Aspen, and Maple. The Hemlock is entirely wanting.

The early foresters in New England generally were in agreement about the distribution of white pine in the pre-settlement forests. According to Spring (p. 21):

> In most situations the original forest [in the pine region of New England] was undoubtedly a mixture of hardwoods and pine, in which the former composed the greater part of the stand upon the better soil of the low hills that characterize the topography of the region. On the lower elevations and poorer soils, especially on the sandy plains, pine formed the greater part of the forest.
>
> In situations where the hardwood growth was predominant, the pine occurred singly or in groups throughout the forest. These pines had a better development than those on the plains, owing to the better soil and their struggle with the hardwoods.
>
> This type of mixed stand exists now in the second-growth forest. The number of pines varies from a few scattering specimens or groups to 50 per cent of the stand.

The pre-settlement forest of southern New Hampshire, as described by Lyford and Margolin (p. 175), was as follows:

> Along the river valleys and on the sandy soils in the eastern part of Rockingham County, white pine was predominant, with red and pitch pine occupying the drier, gravelly soils. On the higher elevations, with a lower limit approximating the 1,500 foot contour, red spruce found its home. The intermediate uplands, comprising the bulk of the area, supported a growth of mixed hardwoods and hemlock, with white pine scattered singly or in groups. In the swamps, which although small, are common at all elevations, grew red maple, black and white ash, black gum, balsam, spruce, tamarack and, near the coast, white cedar.

Lyford and Margolin's ideas concerning the site requirements of white pine were restated in somewhat more detail as follows (p. 185):

> White pine is common at all elevations below 1500 feet. It is adapted to a variety of soils, but grows most rapidly where the supply of moisture is plentiful and the soil well drained. On dry, sandy soils there is less competition from other species, and pine is more abundant, but its growth is slower. It cannot endure the excess of moisture in the swamps or the salt sea-breezes near the coast.

Old Field White Pine

Clearing of the forest within the range of white pine for plow land and pasture and a subsequent abandonment of these fields often produced pure stands of even-aged white pines. Sargent (1884, p. 500) described the old field origin of pine stands in New England, where they were widespread:

> Abandoned farming land, if protected from fire and browsing animals, is now very generally, except in the immediate vicinity of the coast, soon covered with a vigorous growth of white pine. The fact is important, for this new growth of pine promises to give in the future more than local importance to the forests of this region.

A similar observation by Pinchot and Graves was made in Pennsylvania (p. 16): "Old clearings and abandoned pastures, if they can be reached by the winged, wind-blown seed of some old tree, grow up at once with an incipient forest of young [white] pines".

Spalding, Graves and Fisher, and Lyford and Margolin mention white pine stands that originated on abandoned fields; and Spring made a detailed study of old field white pine stands in New England. Spring described the formation and early development of an old field white pine stand as follows (p. 19):

> Many abandoned farms in the white pine region, notably those in southern New Hampshire, have reverted to pine forest. Cultivated land, when

> it is abandoned, is soon covered by blackberry vines, grass, and weeds, which, on a loose, well-worked soil form a ground cover of uniform character. Whether a stand of pines will then occupy it depends upon the presence of seed trees. Meadow land, except that situated on rich river bottoms, also offers favorable conditions for the extension of pine, and regular, well-stocked stands often result from one good seed year. Land kept in pasture for many years and closely grazed does not afford so favorable a seed bed when it is abandoned, because of its compact soil and the character of its ground cover. When reproduction of pine takes place the seedlings are likely to occur in groups, on favorable spots unevenly distributed over the pasture. The blanks may be filled by the seeding of subsequent years, but in some cases they resist invasion for a long time.

Spring stated that most pure stands of second growth pine in New England were of old field origin and offered the following explanation for the phenomenon (p. 21):

> The term "pure forest" is commonly extended to include any stand in which at least 80 per cent of the trees are of one species. Most of the second-growth pine in New England is composed of such stands, which have arisen almost entirely by the establishment of white pine on farm land. In many instances the land originally bore hardwoods, but after its moderate fertility was exhausted by agriculture it became better suited to the growth of pine than to more exacting species.

Summary

Sargent subdivided the forests of the Atlantic region of North America into six categories, one of which was the Northern Pine Belt, "characterized by the white pine (*Pinus Strobus*) its most important, if not its most generally-distributed, species" (1884, p. 4). This forest consisted predominantly of deciduous trees (Sargent, Spalding, Graves and Fisher, Pinchot and Graves, Lyford and Margolin) with pure stands of white pine being largely confined to areas of sandy soil and sand plains (Sargent, Spalding, Spring, Lyford and Margolin) and abandoned fields (Spring, Lyford and Margolin).

In the existing forests, both the remnants of the pre-settlement forest and the second growth, white pine trees could be found on almost all kinds of soil materials and in almost all topographic positions (G. B. Emerson, Pinchot and Graves, Sargent, Spalding, and Spring); but usually were absent from soils derived from limestone (Hough), heavy clay soils (Spalding), areas exposed to salt air (Lyford and Margolin) and, in southern New Hampshire at least, swamps (Lyford and Margolin). However, Emerson thought that white pine "prefers a situation moderately dry", and Spalding thought it "prefers [a soil] with a fair admixture of sand, insuring moderately rapid drainage". Emerson and Hough believed white pine grows best on sandy soil — deep, moist and loamy (Emerson), or with a clay subsoil (Hough). Others (Sargent, Spalding, Lyford and Margolin) believed that white pine grows best on rich, moist, but well-drained soil, or, as described by Spalding and Spring, on the "better soils", mixed with hardwoods.

The old field origin of pure stands of white pine in New England was well known (Sargent, Spalding, Egleston, Graves and Fisher, Spring, Lyford and Margolin). Spring noted that many of these old field pine stands grew in places that formerly supported hardwoods, and he attributed the change to soil exhaustion resulting from agricultural practices.

Records of forest successions involving alternations from pine to hardwood stands existed (G. B. Emerson, Thoreau, Hough, Egleston, Pinchot and Graves, Graves and Fisher, Pinchot), but the reverse had also been reported (Emerson, Hough, Pinchot). The early observers tended to explain pine-hardwood successions in terms of lack of pine seed for regeneration after cutting (Spalding, Graves and Fisher), or the presence of an understory of other species (Emerson, Thoreau, Pinchot and Graves), which might result from the inability of pine seedlings to grow in dense shade (Graves and Fisher, Spring). Emerson, however, believed successions resulted largely from exhaustion of nutrients, and Hough believed they resulted from climatic changes or accidents of seed dispersal that placed a species in a site that approached the optimum for its growth. In general, the emphasis was upon seeds and seedlings; and though Pinchot and Graves in effect described a pine-hardwood succession at the most critical stage in its development — the suppression and death of white pines at 12 to 15 years by sprout hardwoods — the possibility of pine-hardwood successions resulting from rapid height growth of hardwood sprouts apparently was not fully recognized. Once germinated, the shade endurance and rapid height growth of white pine seemed to assure its successful regeneration, even in mixture with hardwoods. Indeed, Spalding recommended that white pine be grown in mixture with hardwoods. It was perhaps too easy to assume that records of pine-hardwood succession were the result of a lack of pine seed.

The early New England foresters were in general agreement as to the best methods of cutting the existing woodlands. They recommended improvement cuts in immature stands to increase their value (Graves and Fisher, Spring, Lyford and Margolin). They emphasized that the problem of stand reproduction required different methods of cutting, depending primarily upon the composition of the stand. Predominantly hardwood stands should be cut by some sort of selection method or coppiced (Graves and Pinchot). Management of mixed stands of white pine and hardwoods presented more problems, and the final cut must recognize the fact that hardwoods sprout and conifers do not (Lyford and Margolin). Pure or predominantly white pine stands should be harvested by some kind of modified clear-cut (Graves and Fisher, Spring, Lyford and Margolin), preferably in a seed year (Spalding, Spring, Lyford and Margolin), that would leave behind on the area an adequate source of white pine seed. Nevertheless, regeneration might require the planting of white pines (Spalding, Lyford and Margolin).

The modified clear-cut method of harvesting white pine woodlots apparently was recommended on the basis of observations that pine seedlings generally were absent under dense stands of pine and hardwood (Spalding, Spring), but were abundant in open areas provided a seed source existed nearby (Sargent, Spring, Pinchot and Graves, Graves and Fisher, Lyford and Margolin). Nevertheless, the details are somewhat conflicting. White pine seedlings could be found under oaks (Spalding, Graves and Fisher), but were absent under maple, birch, and beech (Spalding). In New England, pine seedlings often were observed under gray birch (Graves and Fisher, Spring, Lyford and Margolin). Low density hardwood stands, apparently without regard to composition, often contained pine seedlings (Spring). Pine seedlings were observed under dense pine stands (Spring) and under mixed pine and hemlock stands (Pinchot and Graves), but they failed to survive under a dense canopy (Spring) unless they received side light (Pinchot and Graves). Pinchot and Graves stated that pine seedlings that had grown in shade would die if suddenly exposed by removal of the overstory.

The first requirement for natural regeneration of white pine was the arrival of seed on the area and its germination. Organic litter overlying mineral soil might inhibit seed germination or subsequent establishment of the seedling (Graves and Fisher, Lyford and Margolin). The short life of pine seed in nature might result in absence or delayed appearance of pine reproduction, particularly if the stand were cut without regard for seed years (Spalding, Spring).

The belief was generally held that the chief factor limiting survival of young white pine seedlings was light. Sargent and Spring believed that shade was required, or at least beneficial, during the earliest period of seedling growth. Although white pine seedlings generally attained a total height of less than a foot during the first five years, their subsequent height growth was rapid (Spalding, Spring, Lyford and Margolin).

Pinchot and Graves, Spalding, Graves and Fisher, and Spring stated that the seedlings were shade-enduring; but Spalding and Spring stated that white pines are not as shade-enduring as some other species. Spalding, Graves and Fisher, and Spring, believed that pine seedlings nevertheless would survive because of their rapid rates of height growth. Spalding, and Graves and Fisher recommended periodic thinning or weeding operations in the young pine regeneration to assist its survival. In contrast to most workers, Lyford and Margolin believed that white pine seedlings were only moderately tolerant of shade, requiring abundant light after the fifth year. However, they attributed the survival of white pine trees in existing mixed stands to their rapid height growth.

Because at this time no white pine stand in the United States had been reproduced and carried through even to the point of canopy closure by silvicultural methods, all silvicultural recommendations were theoretical. It was natural and logical for early American foresters to put first things first: to concern themselves with methods of harvest that promised regeneration, and to study the characteristics of seedlings and the various agents that might interfere with their early survival. Other problems, and there might be many in the long time span peculiar to the nurture of plants having tree form, could be solved as they appeared. The general optimism of these foresters was based upon their interpretations of observable silvical characteristics of the different species, plus a belief that any possible sources of trouble could be controlled. In view of European success in forest management, this optimism would not appear to be unwarranted.

The foregoing review of silvicultural systems and silvical knowledge is not intended as a reconstruction of the materials and ideas upon which management decisions actually were made at the Harvard Forest in 1908. With the exception of Lyford and Margolin's work, indirectly referred to by Fisher in Harvard Forest Bulletin No. 1, there is no concrete evidence that these materials were ever used by the Harvard Forest staff. However, it is highly probable that at least some of these reports provided source material for ideas and possibly provided some basis for making management decisions. The silvicultural recommendations they presented were theoretical. Nevertheless, as a body, these reports fairly exude optimism.

From a fifty-year vantage point, it is, of course, easy to pick and choose among this mass of ideas, observations, and conclusions those which at the present time seem valid. The fact that so many careful observations were recorded at this early date is a measure of the keen way in which the problems of forestry were attacked. Extrapolations from mature trees to seedlings were bound to be erroneous in part, particularly when space had to be substituted for time. But the Harvard Forest was about to launch a system of dogged experiments which would put the element of time into observations made at a single point in space, and the results would remove much of the need for substituting space for time in the analysis of woodlot management.

THE WHITE PINE ERA AT THE HARVARD FOREST

First Operations

The first cuts in the Harvard Forest were made in the winter of 1908–09, and involved 1) a pure stand of white pine, 2) a mixed stand of white pine and hardwoods, and 3) a hardwood stand. The over-all management policy was still in the formative stage, but the stated aims clearly reflected the necessity of balancing long-term silvicultural goals against current economic necessity (Fisher, 1911, p. 1):

> At the outset, pending the completion of the working plan, the amount of the cut was determined partly by a rough measurement of the growing stock and estimate of the growth, and partly by silvicultural condition, salability, and considerations of local policy. It was decided to cut about 200,000 feet of lumber (which was well within the annual increment from the tract), and 200 cords of firewood. . . . The intention was to do just as much improvement cutting, yielding an inferior grade of lumber, as was consistent with securing a fair price for the main cut of mature timber.

The white pine stand was dense (40,000 board feet per acre), about 60 years old, and contained about 10 percent by area of hardwoods occurring mostly in small groups. Needle litter and a thin layer of humus mantled the mineral soil, and "a partial reproduction of hardwood seedlings, chiefly white ash, sugar maple, black cherry, red oak, and chestnut, had already started" (Fisher, 1911, p. 2). It was decided to thin the stand with the hope that pine reproduction could thus be established and the growth rates of the remaining trees increased. To accomplish this, "all overtopped and suppressed pines, a good many of the intermediate, and such dominant trees as were in poor condition, or excessively wide-crowned" (p. 2) were removed. All hardwoods were also removed, unless removal "would leave too large an opening" (p. 2). In silvicultural jargon, this operation comprised "a combination of preparatory and seed cutting under a Shelter-wood System with Uniform Cuttings" (p. 2). Fisher believed that the small amount of slash that resulted from the cuts would not hinder reproduction or create a serious fire risk.

White pine comprised about 75 percent of the mixed pine and hardwood stand, which also was about 60 years of age. The trees ranged in height from 80 to 90 feet. The condition of the forest floor was described by Fisher (1911, p. 6):

> The leaf litter was 3″ to 6″ in depth, and the humus 2″ to 4″. There was already a large reproduction of well-distributed hardwood seedlings on the ground, of which white ash, black cherry, red oak, and chestnut were the chief species. Moreover, these seedlings were for the most part less than a foot high, and consequently not likely to be seriously injured in the logging. Reproduction of pine was practically wanting, as is usually the case in such heavy, dark stands. . . .

The year 1908 was a heavy seed year and, according to Fisher (p. 6), "it was therefore expected that by cutting the stand clear, and burning the heaviest of the slash, a reproduction of mixed pine and hardwoods would be secured". Fisher elaborated his ideas concerning mixed stands, and his remarks suggest that natural regeneration of mixed stands was a controversial matter (p. 6):

> Such a mixture is without question the most valuable and productive for good situations, both in the quantity of wood produced, and in the quality of the timber. The certainty of the reproduction, of course, cannot be guaranteed, but in many cases, where a similar operation has coincided with a seed year, a satisfactory new crop has followed, even without any attempt to dispose of slash. In any event, from one-third to one-half of a full stocking will be furnished by the hardwood reproduction, and in case of a failure of the pine, seedlings can be very cheaply planted next to the stumps of the old trees, thereby securing a favorable spot for growth, and partial freedom from possible suppression by hardwood sprouts.

Admitting the uncertainty of the results, Fisher argued that the method was cheapest, that the necessity of slash burning could be charged at least in part to protection, and that "the form of the stand and the mixed crop with which it is to be replaced make any method by partial cutting almost impracticable" (1911, p. 7). He elaborated his objections to alternative silvicultural methods (pp. 7–8):

> If scattered seed trees from such a dense tall forest are left, they are very apt to blow down, and before they have finished seeding up the ground, the hardwood reproduction has got too great a start. Group or Shelter-wood cuttings tend unduly to increase the percentage of hardwoods, and Selection cutting is still more unsuited to the silvics of the desirable species, pine and chestnut. On the other hand, when such a forest as this is cut down immediately after a fall of seed, from one half to a full stocking for the ground

is assured, supplementary planting (if needful) is cheaply done, and the resulting combined crop begins effective growth almost at once.

The hardwood stand, "representing the gradual extension of a temporary type over land which fifty years ago was partly pasture" (Fisher, 1911, p. 4), consisted largely of "red maple, large-toothed poplar, gray and paper birch, chestnut, red oak, and hard maple, with scattering white pine. Almost everywhere there was an excellent reproduction of valuable hardwoods and white pine, some of it already in the sapling stage". An improvement cut and thinning was made here. In places, the cut was heavy and damaged the reproduction, but "even that injured was left in condition to sprout again". The slash was scattered over the ground.

The first cutting operations at the Harvard Forest thus followed a conservative silvicultural policy of reproducing, not converting, the stands. Although white pine was the most valuable tree growing in the Forest, no attempt was made to convert the hardwood stand to pine, or the mixed pine and hardwood stand to pure pine. In all three stands cut in 1908–09, the advance growth consisted overwhelmingly of hardwoods. Thus the fundamental problem in the regeneration of two of the stands was the introduction of significant amounts of white pine seedlings. Fisher hoped to solve this problem without recourse to planting. By making cuts in a seed year he hoped to catch sufficient pine seed to accomplish this goal. By increasing the amount of light reaching the forest floor and by mixing the organic litter with mineral soil to make a better seedbed, he hoped to create an environment suitable for the growth of pine seedlings. He mentioned the possibility of failure, but believed that pine seedlings could be ". . . . very cheaply planted next the stumps of the old trees, thereby securing a favorable spot for growth, and partial freedom from possible suppression by hardwood sprouts" (1911, p. 6). The problem of site in relation to seedling establishment had yet to arise.

Initial Results of the First Reproduction Cuts

The white pine seed year of 1908 was followed by a summer drought in 1909. This piece of bad luck obscured the results of the regeneration experiments. By the fall of 1909, pine seedlings had "come in abundantly almost all over the cutting" (Fisher, 1911, p. 2) in the pure pine stand. A series of 8-foot-square sample plots contained from 16 to 65 pine seedlings, but the "color and condition" of the plants was subnormal. The poor condition of the seedlings was attributed to reduced light under the shelterwood and to the needle mat "through which the rootlets were not easily able to reach mineral soil" (p. 4).

Pine seedlings were less abundant in the fall of 1909 in the clear-cut area of mixed pine and hardwood, but Fisher thought (1911, p. 6) that "the results of this clear cutting were as successful as the unfavorable growing season of 1909 would lead one to expect". In June, 1909, only 2 to 12 pine seedlings were found per 8-foot-square sample plot, but these were "exceptionally thrifty". Of these, nearly half had "dried out and died" by fall, presumably because of the summer drought. Fisher believed that "in ordinary seasons a sufficient number of seedlings to restock the ground would probably have survived" (p. 7). He further analyzed the survival of seedlings in terms of litter and micro-habitat relations (pp. 6–7):

> Those still living, many of which had made remarkable growth, were situated either where the leaf litter and humus had been well mixed with the mineral soil, in small moist depressions, or where there had been side shade from weeds or the adjacent woods during the hot part of the day. The plants which had died had stood chiefly on the south side of small hummocks or where the thick mat of needles and humus had not been disturbed.

The pine seedlings growing under the shelterwood showed increased vigor in 1910, and by the end of May, 1911, showed much promise. According to Fisher (1911, p. 4), "considering only density and health, the new crop is already effectively established". This conclusion was tempered by concern over the effect of the final cut (p. 4): "The effect of removing the old stand, with the attendant damage and increase of light, has yet to be demonstrated".

By the fall of 1912, the regeneration in all three areas was generally in an unsatisfactory condition because of the rapid growth of hardwood sprouts.

In the hardwood stand, poplar root suckers, as much as 15 feet tall, were abundant, particularly in the more open areas (Heald, 1912). Sprouts from the hardwood seedlings that had been cut back during the 1908–09 cuttings, so-called seedling sprouts, were not abundant. In places, beds of fern were so dense that further regeneration seemed to be inhibited. Oddly enough, the best hardwood reproduction was under a group of medium-aged white pines from which the larger hardwoods had been removed in the cutting operations.

In the pure stand of white pine, sample plots 8 feet square showed 2 to 33 white pine seedlings per plot, but their needles were generally yellowed and brittle (Tryon, 1912). Tryon attributed the unsatisfactory condition of most of the pine seedlings to insufficient light resulting from the dense growth of advance hardwoods and to the presence of a thick mat of organic litter, because the seedlings appeared much healthier in large openings and in places where organic litter had been disturbed. He noted a great increase in height growth of the hardwood reproduction since the cutting, and concluded that "The pine seedlings are hopelessly out of the race now, unless some very expensive method of removing the hardwood is put into practice". He believed that the management aims should be re-examined, and recommended that the new stand be managed as a hardwood stand. Because of the "discrepancy in the size of these two occupants of the floor", he thought that the creation of a mixed stand of white pine and hardwoods was "out of the question". One of his reasons for abandoning the attempt to form a pine stand constitutes a forcible statement of the hardwood sprout problem:

> . . . in order to fully liberate these pines, this hardwood growth would have to be either removed bodily, or else the main stems broken off, not cut clean, in order to prevent their sprouts from absolutely ruining any chance of the young pine coming through. Such a practice would be attended by an obviously prohibitive cost.

Nevertheless, Tryon believed that if the cuts had been concentrated in small areas, the growth of the pines would have been promoted, and the hardwoods would have been reduced in numbers.

In the mixed pine and hardwood stand, white pine seedlings were in fifth place, outnumbered by white ash, elm, black birch, and black cherry stems. Whereas red maple, white ash, and chestnut reproduction averaged 8 to 10 feet in height, the white pine seedlings averaged only 10 inches. According to an inspection report in the Harvard Forest records, "A large portion of pine has either died of drought or has been checked by the growth of weeds and sprouts". Therefore, in 1912, maple, poplar, birch, cherry, and chestnut sprouts were cut back to release the pine seedlings, with the aim of establishing a mixed stand consisting predominantly of white pine, white ash, black cherry, and red oak.

Lutz and Cline (1947) have described in detail the further operations and changes in the clear-cut mixed pine and hardwood stand (Case No. 1) and in the shelterwood-cut pure pine stand (Case No. 2). Both stands eventually became hardwood stands in spite of continuing efforts to maintain the white pine. By 1930 the shelterwood-cut pure pine stand had been written off as a mixed pine and hardwood stand (Harvard Forest records):

> A few groups of white pine in the southern end . . . were opened up, but for the most part the stand was mixed hardwoods, running strongly to red oak, paper birch, and white ash.

By 1933 the Harvard Forest staff had bowed to the inevitable and, not without some pride, had recognized the young stand that followed the clear-cutting of the mixed pine and hardwood stand as a hardwood stand (Harvard Forest records):

> At the time of the present operation [February, 1933] only two small groups of pine remained (along the brook); all other pines were thoroughly suppressed and out of the running. The stand was one of the finest examples of volunteer hardwoods following a pine cutting to be found in this section.

The hardwood stand recovered from the burst of poplar root suckers and, in spite of chestnut blight and the hurricane of 1938, by 1946 constituted "a fairly good, if unpremeditated, example of a selection forest" (Spurr, 1946, case history).

Early Research in Site Characteristics

The cutting methods that had been applied to the pure and mixed stands of white pine in 1908–09 had accomplished the initial objectives of natural regeneration. White pine seed had been made available and, on the whole, had resulted in a number of young pine seedlings that was adequate to reproduce the stands. But the observations, first recorded in the inspection reports of 1912, concerning the relative rates of height growth of the pine seedlings and the associated hardwood sprouts dramatically underscored the serious problem of hardwood "competition". Apparently these observations served as a strong stimulus to thought, because the next few years marked the beginning of research activity, as distinct from experimental applications of existing silvicultural systems, at the Harvard Forest. Some of the studies have a direct bearing upon the problems considered in this review.

Studies of Regeneration in the Cutover Pine Woodlots

Within ten years after the first cutting operations at the Harvard Forest it became clear that most of the pine woodlots would be succeeded by hardwood stands unless severe measures were taken to control the hardwood reproduction. Neither the relatively high "shade tolerance" claimed for white pine by the early foresters nor the rapid height growth of pine seedlings after the fifth year was enough to assure their survival when growing in mixture with young hardwoods. Studies were made of stands up to fifty years of age that had followed the cutting of pine woodlots in a large area in central New England (Fisher, 1918b; Terry, 1918). The evidence was quickly digested and resulted in the silvicultural recommendation of early and continuous improvement cuttings or weedings in the young stands. This recommendation was forcefully presented by Fisher (1918b), and adopted as policy at the Harvard Forest.

These studies of the volunteer stands that followed the cutting of pine woodlots are of particular interest to the present review because they suggest for the first time that the results of attempts to regenerate pine may depend upon the nature of the site. Prior to these studies, observations relating to site characteristics were more in the nature of general descriptions of areas, although a realization of the importance of seedbed conditions had resulted in detailed descriptions of the organic litter. Thus, though the earliest records and student reports noted such site characteristics as topography, slope orientation, and soil texture, these things were recorded largely without comment or interpretation. An increased interest in site evaluation is apparent in 1912, when the students were making strip topographic maps showing forest composition and condition, and noting such soil characteristics as texture, thickness of mantle, general moisture conditions, and nature and thickness of organic layers. A body of observation on relationships between forest composition and site components was being assembled, although no pressing need for such material was yet felt. White pines grew almost everywhere, and the solution of any regeneration problems was thought to lie entirely in the realm of silvicultural manipulation in the young stands.

Fisher (1918b) presented plot data showing reproduction in an area that had been clear-cut in a pine seed year, the slash having been burned. At the end of five years, of 530 seedlings in a 1/16 acre sample plot, only 62 were white pines. In addition to the hardwood seedlings, 146 hardwood sprouts were present. Furthermore, "although the white pine and many of the valuable hardwoods in this sample plot were still thrifty, they were already overtopped and plainly soon to be suppressed entirely" (p. 495). Measurements of the height of 800 trees of various species, ranging in age from 1 to 6 years, on a site rated as "Quality I" showed that (pp. 503–504):

> . . . in general, the dominant new growth on a cut-over area will be

> between 12 and 15 feet in height (at the end of six years), when white pine of the same age and not retarded by overhead shade will have reached the height of only four feet. Furthermore, owing to dense and bushy development, the sprouts of desirable species like white ash may be quite as worthless in prospect as those of red maple. Between the two extremes of height growth, as represented by the hardwood stump sprouts at one end and the white-pine seedlings at the other, there will be a large amount of other seedling and sapling reproduction, . . . much of the best of which will be nearer the normal rate of white pine than the excessive rankness of the sprouts.

Study of older stands that had followed the cutting of pine woodlots showed variations in composition and growth rate apparently related to site variation. Thus, a 20-year-old stand growing on the "poorest" site examined, "a flat, rapidly drained area on the edge of a small sand-plain", showed a relatively small amount of sprout growth, and "about half the white pines on the area . . . were still vigorous enough to make normal growth if released" (Fisher, 1918b, p. 498). Although Fisher believed that this site was "distinctly less favorable for the better hardwoods than any of the other situations considered" (p. 498), he noted that most of the pines were less than 15 feet tall, whereas some of the hardwoods were more than 25 feet tall. A 40-year-old stand showed much the highest number of suppressed pine trees in the series. According to Fisher (p. 501):

> This plot represents soil of quality I — a site distinctly more favorable for hardwoods than for pines. The figures show that suppression proceeded here much more rapidly than on the lighter, sandier soil of Plot II [the 20-year-old stand]. The 413 trees in class C [completely suppressed or dead] were all dead, for the most part about twenty years old and between 10 and 15 feet in height. These were almost exactly the general dimensions of the B trees [overtopped but still capable of recovery] in Plot II, which, nevertheless, though completely overtopped, would most of them have survived from five to ten years longer on the poorer soil.

By projecting the expected results of weeding through a 60-year rotation, Fisher was able to estimate final yields of white pine sawtimber for each of the different age classes studied. His calculations showed that yields would be nearly tripled on sandy soils by making a release cutting at 20 years, and "that an earlier cutting would produce a still better result, especially on the better soils" (1918b, p. 502). For "best results in the forms of final value", Fisher (p. 504) recommended weeding before the sixth year, and stated that at the Harvard Forest best results were obtained by weeding during the third or fourth year. The frequency of subsequent weedings depended upon (p. 504):

> . . . composition — that is, how vigorous and numerous the desirable trees are in comparison with the undesirable — and, second, on the quality of the locality. The better the site the more rapid and persistent will be the growth of the hardwoods that must be eliminated. The general object should be to maintain the largest possible proportion of valuable trees in favorable growing condition until they have reached a size and rate of height growth that will enable them to keep even with or ahead of the weed element in the stand.

Citing experience at the Harvard Forest, Fisher noted that equality of height growth was reached after the eighth growing season. During this period, two weedings had been applied; and by assuming that no more would be needed, Fisher was able to state that the cost of weeding "is many times justified by the final return" (p. 505).

Terry (1918) studied the natural regeneration in cutover pine woodlots on the Harvard Forest as well as in 54 other woodlots that had been cut in the period 1905 to 1909 in other parts of northern Worcester County, Massachusetts, and the adjacent parts of Cheshire County, New Hampshire. A summary of results was published in 1920 (Fisher and Terry, 1920). Of the 54 woodlots, only 14, all of which were cut in a seed year, showed as many as 500 pine seedlings per acre. The study showed that "general site factors such as slope and aspect had little or no effect, but that the condition of the seedbed was apparently of first importance" (p. 359). Nevertheless, past use of the land and characteristics of the soil materials seemed to be important (p. 360): "Outstanding facts were that on all but the lightest of the local soils, the hardwoods are gaining, and that the composition of the present forest types has been controlled in the main by the previous treatment of the land". The cutover lands further showed that in all areas examined, success in obtaining natural regeneration was only the first step in reproducing the stands: "However successful the reproduction may be at the start, within 10 years from 10 to 80 per cent of the desirable elements, both pine and hardwood, was overtopped and suppressed by inferior species and clumps of stump sprouts".

Composition and Field Relations of Pre-settlement and Second Growth Forests

One of the earliest investigations was concerned with the reconstruction, from evidence on the ground supplemented by historical material, of the nature and distribution of variations in the pre-settlement forest

(Fisher, 1916). The first results of these studies confirmed the general belief that the pure stands of white pine had originated almost entirely on abandoned farmland. The forests in the town of Petersham, covering at least four-fifths of the land area, were almost all less than 75 years of age, and most of them ranged from 40 to 60 years. Most of the pure stands of white pine were "noticeably geometric or straightsided in shape" (Fisher, 1916, p. 191). According to Fisher:

> Such stands, owing to the seeding habits of the white pine, originate only on cleared land — pasture, old field, or in rare cases, burn. . . . In the absence of evidence of fire, these blocks of pine thus fix the approximate date of a general abandonment of farm lands — lands still further identified as such by the incongruous lines of stone walls and occasional cellar-holes now buried in the woods.

Fisher believed that probably 90 percent of the land surface of central Massachusetts was mantled by forest at the time of settlement by white man, between 1700 and 1740; and "by 1850, fully three-quarters of the forested area had been cut over at least once, and over half of it cleared for farms" (p. 192). Then the population began to decline, because of such things as "the building of the Fitchburg Railroad, the development of manufacturing towns, . . . the opening of the West", and a war-time emigration "for the defense of the Union". Then, "the forest flowed back over the fields, so that today there is nearly twice the area of woodland there was in 1850, and at least as much as there was in 1800".

Studies of pine woodlots in New England showed that 90 percent of the stands had originated on "land formerly farmed or pastured" (Fisher, 1918a, p. 253). According to Fisher, "only under exceptional conditions, such as very sandy soil or the effects of a timely fire, has pure pine survived to maturity on other than cleared land". However, all abandoned farmland did not support pine stands, and Fisher sounded a note of caution (p. 254): "In drawing conclusions from the life history of these pine woodlots, it is usually overlooked that the existing stands give no hint of the number that failed to materialize through unfavorable influences".

The comprehensive studies of regeneration following the cutting of the pine woodlots apparently affected the thinking concerning the nature and distribution of the pre-settlement forest and its descendents. Thus a general description of the pre-settlement forest stressed a relationship with the characteristics of the soil materials (Fisher, 1921, p. 8):

> When the country was first settled the composition of the forest was very different from what it is today. From small fragments of the original

> forest which still exist, and from scattered documentary evidence, it is clear that the primeval condition was almost everywhere a mixed and many aged stand, containing both hardwoods and softwoods. White pine and hemlock made up the bulk of the softwoods, the pine occurring as a very tall and scattering overwood under which grew in great variety of size and age, hemlock, white ash, red oak, and the other hardwoods. This original forest, covering probably ninety per cent of the land area, tended to become pure hardwood on the deeper, moister soils and to merge into almost pure softwood on the upper slopes or drier, sandy situations. When the first settlers came there was probably very little pure pine in the locality.

This same body of ideas permitted a further refinement of thought concerning the origin of the white pine woodlots (Fisher and Terry, p. 358):

> The so-called pine woodlots, which make up about four-fifths of the timber cut in central New England, are usually even-aged, and contain from 50 to 100 per cent white pine. Almost without exception these stands have originated on vacant land, abandoned pasture, or mowings, sites which, prior to the settlement of the region, bore forests either of hardwood alone or mixed hardwood and softwood. Except for occasional sand plains and thin-soiled summits, the areas which now bear mainly white pine are usually natural hardwood sites. The result of this is seen in the tendency of cut-over lands, so often remarked, to revert to hardwood. At the time of cutting, which is commonly at an age varying from 50 to 70 years, over 90 per cent of the second growth pine lands contain an abundant advance growth of hardwoods and, in the case of the stands of deficient density and on the moister soils, sometimes heavy thickets of underbrush or woody ground cover. Pure pine in the woodlot region is a transition type.

Significance for Silviculture

The comparative studies of the mixed regeneration in the cutover white pine woodlots constituted a milestone in white pine silviculture. These in combination with the studies of the origin of the pure stands of white pine on the uplands provided the key to forest management at the Harvard Forest. Survival of pine seedlings in mixed stands on cutover areas was found to be related to site variations, chiefly differences in the soil materials, which could be measured indirectly by measuring the height growth of the seedlings. The effects of soil variations upon pine seedling survival were eliminated by land clearing followed by land abandonment. Thus, old fields commonly supported pure stands of white pine for one generation regardless of the nature of the soil materials.

On sites where hardwood seedlings and sprouts grew rapidly, pine seedlings were soon suppressed or killed. The pines might be saved by removal of the overtopping hardwoods; but on the better sites and better soils (as measured by height growth rates), the treatments must be thorough and often repeated. The problem thus became an economic one.

The presence of pure stands of white pine on sand plains could be explained in terms of slower rates of height growth of hardwoods relative to pine and reduced rates of sprout formation. On heavier soils, pure stands of pine were the result largely of the past use of the land. However, the origin of scattered large white pines in otherwise deciduous forests remained a problem, particularly when they were growing upon heavy soils.

The careful rating of species according to light requirements lost much of its meaning as a result of these studies, and the significance of site variation for the culture of white pine emerged from an obscurity brought about by the omnipresence of the species. Furthermore, these studies pointed out the importance of distinguishing between site recognition in terms of stand establishment and site recognition in terms of production rates, once a stand had become established.

Revised Management Policy

The assessment of natural regeneration resulting from a variety of cutting methods led to some modification of the management policies at the Harvard Forest (Fisher and Terry, pp. 361–365). The outstanding change was a shift in the regeneration aims when cutting pure stands of white pine. Fisher and Terry gave several reasons for this change from a goal of pure pine regeneration to mixed pine and hardwood (p. 362):

> Bearing on the composition of a desirable forest crop is the fact that the present pine woodlots are transition types and as such are difficult to maintain. Furthermore, the market for the better hardwoods has greatly improved, and bids fair to improve still more in the near future. In view of these considerations, it has become the silvicultural policy on the Harvard Forest to replace the pure pine type with mixed stands containing, in addition to pine, the best of the local hardwoods, an abundance of which is almost always present on the ground.

The series of experimental cuts pointed toward preliminary thinning followed by a clear-cut (commonly referred to as the 2-cut shelterwood method) as the best means of establishing white pine seedlings. Although clear-cuts simplified logging and milling, the 2-cut shelterwood system provided a hedge against lack of pine seedlings if the final cut was made in a non-seed year, and was believed to reduce the loss from the snout beetle (*Hylobius pales*). The cutting system was not inflexible. Clear-cuts would be made each year; but annual thinnings might be omitted, particularly in seed years. Before the final cut, all advance growth would be mowed close to the ground to increase the quality of the hardwood reproduction, and after cutting clean the slash would be burned.

An essential part of the management of the regeneration was weeding. This was strongly stated by Fisher and Terry (p. 364):

> As a result of experience in the Harvard Forest nothing is clearer than that the critical period for a forest is in the small sapling stage. The money value of the final crop can be more greatly influenced by proper treatment at this time than at any other stage of the rotation.

Weedings would be made in the new crop at ages 3 to 5 years and again at 8 to 10 years. This time span encompassed Harvard Forest experience in the regeneration of cutover pine stands, but Fisher and Terry speculated as to the necessity for further weedings and to variations in the effectiveness of weeding as related to soil differences (pp. 364–365):

> After about 10 years the pine and hardwoods of seedling origin have reached a uniform and roughly equal rate of height growth. Meanwhile, however, the weed elements in the stand will have again become dominant, so that the cleaning has to be repeated. On light, sandy soils a satisfactory result can be achieved with one weeding, applied in such cases after a longer interval. On rich, moist sites it is occasionally necessary to weed the crop a third time, in order that the best advantage may be taken of the very productive land.

An important addition to the concept of weeding was made later by Fisher (1921, pp. 14–15):

> The first weeding is applied in the fourth year after cutting, by which time it is possible to make intelligent choice among the various elements in the stand and to identify the silvical and site factors which are likely to govern composition. For the most part, pine is favored on the drier sites or where the hardwood is scattering. Hardwood is favored on the richer soils or where established in particularly dense groups.

This statement suggests that the composition of the regeneration was the primary consideration in making management decisions, but that the decisions might be modified by the characteristics of the site. Management must be concerned with the existing regeneration. Nevertheless, one wonders if a good catch of pine seedlings on "richer soils" would lead to attempts to control the hardwoods.

Fisher and Terry stated that two weedings had been found economically feasible at the Harvard Forest, but made clear the fact that the final outcome of the management method was unknown (p. 365): "Exact figures bearing on the final yield of such weeded stands of mixed hardwoods and pine are lacking". Arguing from values derived from mill figures on pure pine stands and on mixed stands, they noted that the values of mixed stands varied with the proportion of white pine, and concluded (p. 365):

> It seems fair to assume, therefore, that in a stand where both distribution and mixture have been properly regulated by early weedings, the yield will not only be better in quality, but at least equal in quantity [to] the production of volunteer growth.

It should be noted that these modifications of management policy were all made within the rather rigid frame of the initial working plan (Fisher and Terry, p. 361):

> The cutting method now in practice on the Harvard Forest, though based largely on the outcome of the experiments above described, was adopted with considerable reference also to practical and financial considerations. The rotation for white pine is set at 60 years. As the working plan is based upon the principle of a sustained annual yield, final cuttings have to be made each year. In this respect the property is in the same case as that of a wood-working concern which requires a steady annual supply.

Development of Site Concepts in Relation to the Management of Mixed Pine and Hardwood Stands

The restatement of management policy for the Harvard Forest by Fisher and Terry recognized the importance of site evaluation in the intensive management of young stands. At this time there were few tools available for site analysis. That is to say, few detailed studies by specialists in the various components of site had been made in the area. But topographic maps, one of the basic requirements for terrain analysis, were available. In addition to the U. S. Geological Survey 15-minute (scale, 1:62,500; contour interval, 20 feet) topographic map coverage, there existed large-scale topographic maps of the Harvard Forest proper. These maps were made between 1908 and 1912 by the staff and students, and showed the Forest at a scale of 1:4,800, contour interval, 10 feet. A detailed map of the bedrock with accompanying descriptions was also available, mapped at a scale of 1:62,500 (Emerson, 1917).

At this time, no map of soils or glacial deposits in the Harvard Forest was available. Nevertheless, the general topographic distribution of the major variations in the soil materials was known (Fisher, 1920, pp. 6–7):

> The general topography and geological history of the region have brought about somewhat peculiar conditions of soil. As a whole, this part of the state is a plateau or pene-plain made up of a series of rather flattened ridges trending north and south. . . . In the main the underlying formation is granitic, and on the ridges outcrops are frequent. The relative elevations are between 1100 feet, which is the general level of the ridge tops, and 700 or 800 feet, which is the altitude of the intervening valleys. The highest elevation on the Forest, Prospect Hill, is 1400 feet above sea level. . . . The whole land surface has been extremely flattened and degraded by glaciation. The result of this topography, formation, and geologic influence has been the formation of soils very stony in composition but on the whole heavy, and tending more to clays and loams than to sands, the only examples of which are to be found in small sand plains or gravel deposits near the base of slopes, or along streams in the main valleys.
>
> There is a contrast in soil conditions between the uplands and the lower slopes or valley bottoms which is apparently the direct result of ice action. As is usual the deepest and richest soils are in the valleys and on the lower slopes.

Perhaps it should be pointed out that the studies reviewed in this section, while selected primarily because of their connection with site problems, constitute an excellent example of an apparently well-planned series of silvicultural studies. Thus, knowledge gained in one study opened up new vistas that were exploited in a second study. Specifically, the difficulties with sprout hardwoods that were apparent by 1912 in the young regeneration led Fisher to an analysis of second growth unmanaged stands, which resulted in a recommendation of early weedings to encourage the survival of white pines (1918b). However, proof that weeding would result in mixed stands of pine and hardwood was lacking.

From this position, one line of research led to analysis of existing hardwood stands, which represented the known product of natural reforestation of cutover lands without benefit of management. Presumably, simple management techniques would at least lead to an improvement of such hardwood stands, even if truly mixed stands were unattainable. Thus Spaeth (1920) made detailed studies of composition, growth rates, and yields in unmanaged hardwood stands that had resulted largely from the cutting of pine woodlots, and Patton (1922) studied in even greater detail the growth and yield of the most valuable of the hardwood types occurring in unmanaged stands as they had been outlined by Spaeth. Averill, Averill, and Stevens (1923) applied the results of these studies to an extensive survey of volunteer, unmanaged stands outside the Harvard Forest.

The second line of research led to detailed studies of certain facets of white pine itself. Thus Peirson studied the life history and control of the pales weevil (1921) and the control measures for the white pine weevil (1922), both of which promised to increase the survival rate and improve the quality of pine regeneration. These studies were followed by careful studies of the growth and quality of white pine as affected by site, density, and associated species (Tarbox and Reed, 1924).

All of these studies, both of hardwood stands and of white pine, were brought together by Cline and Lockard (1925) in a comprehensive evaluation of mixed white pine and hardwood stands that included a consideration of origin and field relations, management, expectable returns, and an examination of alternative methods of growing white pine. This series of studies represents a vigorous attack upon problems that bore directly upon the day-to-day operations of the Harvard Forest within the frame of long-term management policy. It is a thorough examination of the known, in the hope of finding guideposts through the unknown — the attainment of a crop of mixed pine and hardwood by means of forest management that would yield a reasonable return from the investments.

Hardwood stands of the kind described by Fisher in his justification for a policy of periodic weedings in young volunteer stands of mixed pine and hardwood (1918b) were examined by Spaeth, who studied growth rates and constructed yield tables. Forty-eight sample plots in northern Worcester County, Massachusetts, 0.25 or 0.5 acres in area, were located in "fully stocked natural stands of even age", ranging from 17 to 75 years old. The results of this study described the characteristics of natural stands that had resulted from the clear-cutting of pine woodlots and hardwood stands which, according to Spaeth (p. 5), "represent the minimum to be expected under forest management".

Spaeth subdivided the stands into "better second growth hardwood stands" in which such species as red oak, white ash, sugar maple, and yellow birch predominated, and "inferior second growth hardwood stands" in which gray birch, red maple, and poplar predominated. He related the origin of these two kinds of stands largely to human activity. Either might follow the cutting of an old field white pine stand (p. 8):

> If cut at the age of fifty years or more a stand of better second growth hardwood results from the advanced hardwood growth which, at that age,

> has become established under the pine stand. If cut at an age under fifty years an inferior second growth hardwood stand results, due to the lack of hardwood advanced growth and the subsequent reproduction by light seeded species.

According to Spaeth, the sprouting capacity of the hardwoods causes better hardwoods to follow the cutting of better hardwoods, but inferior hardwoods to follow inferior hardwoods only if cut before the stand attains an age of about 30 years. He stated that stands of inferior hardwoods, if left to grow for more than 30 years, slowly change into better hardwoods as the short-lived gray birches die.

Spaeth recognized two different site classes among the "better" hardwoods sampled, based upon the average height of the dominant trees of the stands. Thus, the dominant trees in Site Class I averaged about 50 feet at 50 years, and those in Site Class II averaged about 40 feet. Site Classes I and II were not further described in terms of the characteristics of the environment, although a third class, not considered in the report, was rather carefully defined in terms of topography, thickness of the mantle, soil texture, and the moisture and organic content of the soil (p. 12):

> The thin-soiled, bouldery ridge-tops of third quality, because of their low yield per acre and inaccessibility have never been clear cut, and on sandy soils, deficient in organic content and moisture, the competition of white pine and inferior hardwoods is such as to exclude the better hardwoods.

Averill, Averill, and Stevens studied the forests in seven central Massachusetts towns by means of a series of east-west traverses located one mile apart, covering a total area of about 145,000 acres. The field data collected included such things as forest type by area, density, age class, site class, and volume. According to the writers (p. 10), "site classes were determined in the field by topography, and by the height of the dominant trees as compared with heights in yield tables". The topographic criteria for site recognition were not further explained. The soils were characterized as "lighter" or "sandier" and "heavier" or "good" or "better", and these distinctions were handled outside the frame of site class (pp. 15–18 and Table XVII). According to the writers (p. 16), the succession of forest types on a single area was related to this "rough classification of soils, mainly physiographic". The physiographic criteria were not detailed, but internal evidence suggests that "lighter soils" refers largely to glaciofluvial sand plains, and that "heavier soils" refers generally to the till-covered uplands.

By tabulating separately the traverses in sandy areas from traverses in "heavier soils", Averill, Averill, and Stevens were able to study the relationship between the different sequences of forest succession and soil texture in 685 cases. Analysis showed that most abandoned fields, regardless of soil texture, developed into the white pine type (80 to 100 percent pine). When these pine stands were cut, they were followed (p. 17)

> . . . by nearly pure hardwoods on 75 per cent of the heavier soils, while on the lighter soils only 46 per cent of the previous pine types are followed by pure hardwoods. Here it will be comparatively easy to perpetuate the pure pine or pine and hardwood types with little more silviculture than clear cutting in a seed-year.

About one-fourth of the pine stands, regardless of soil texture, were followed by the gray birch type (largely gray birch, red maple, poplar, and pin cherry). However, on light soils, stands of the gray birch type were rarely found to be older than 20 years, which (p. 17)

> . . . would indicate that there is a comparatively small percentage of gray birch that will persist on the lighter soils if there are any pine seedlings to compete with it. Just the opposite is true for the better soils, as has been shown by numerous experiments on the Harvard Forest.

Tarbox and Reed studied quality in white pine by means of sample plots in pure pine, pine and hemlock, and pine and hardwood stands in north central Massachusetts and southern New Hampshire. They classified sites on the basis of production rates of white pine, using height over age as the criterion. The results varied with stand composition. For example, on Site I the average height of the dominant pine trees in pure stands was 65 feet at 50 years, but only 57 feet in mixed pine and hardwood stands. However, the average height of pine dominants reached 82 feet at 70 years in both types. By comparison, the average height of dominant pine trees in pure stands growing in areas classed as Site II was 58 feet at 50 years, and only 76 feet at 70 years. An inverse relation between site quality defined in these terms and diameter growth was found in pure stands growing on Site I, which was explained on the basis of crown friction and subsequent crown reduction. Thus, dense stands on Site I showed a rapid diminution in rate of diameter growth between 20 and 30 years as compared with less dense stands on Site I and stands on Site II. The stubbier trees on Site II showed little crown abrasion. However, Tarbox and Reed found that rates of height growth in pure stands were unaffected by density.

Cline and Lockard returned to a consideration of unmanaged stands of mixed pine and hardwoods, examining woodlands in a 2,000 square mile area in north central Massachusetts and southwestern New Hampshire. They concentrated their efforts upon stands of this kind that had arisen following the clear-cutting, in a seed year, of pure stands of old field white pine, and made three important contributions to the problem of management at the Harvard Forest. They identified Site I and Site II, as used at the Harvard Forest, in terms of the properties of the soil materials, and related these differences in soil to stand composition in considerably more detail than had been done previously. Secondly, they observed that the various species constituting the natural regeneration in cutover areas seldom were uniformly distributed, and they emphasized the importance of management of groups within a stand. Finally, they advanced the hypothesis that the occasional white pines present in mature hardwood stands are the result of a natural process of attrition acting upon a group of young pine seedlings, and related variations in this process to site variation defined in terms of soil materials.

Cline and Lockard combined Fisher's 2-way classification of sites based upon soil ("better" soils and "lighter, sandier" soils, 1918b) with site classifications based upon height over age relationships of dominant trees, to give a generalized 3-way subdivision of sites based upon the soil materials (Table 1). Thus, of the "better grades of soils" (Sites I and II), the "heavy" or "richer" soils (equivalent to Fisher's "better" soils) were equated with Site I, and the "medium" soils with Site II. The "lighter" soils of Fisher's usage made up the third category of site.

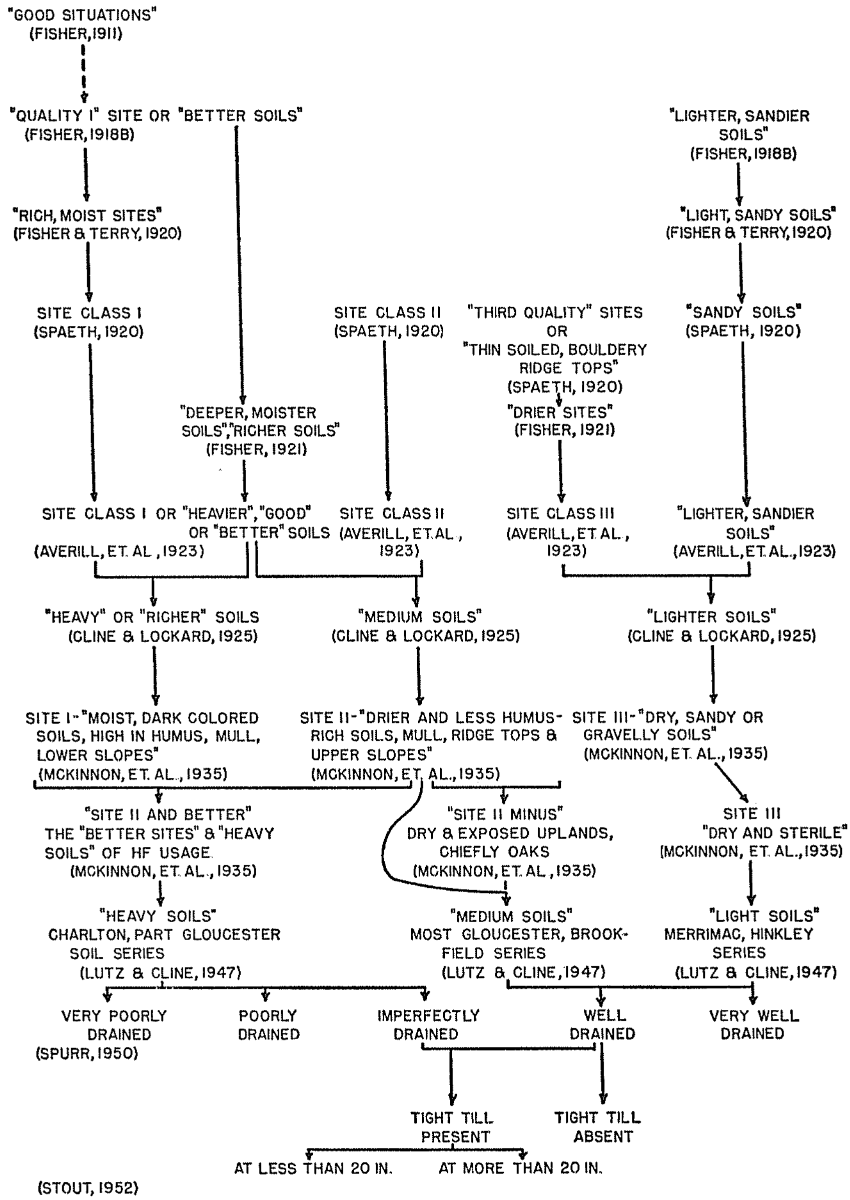
They believed that this classification of site on the basis of soil had significance in forest management, particularly in its relation to composition of the reproduction that follows the cutting of mature pine stands. In regard to this "control of reproduction", Cline and Lockard (p. 37) stated:

> The fundamental factor is soil. On the lighter, sandier soils the softwoods tend to predominate. Conversely, on the richer, heavier soils the hardwoods have all the advantage, so that in such cases there is no question of pine, either actually or potentially. Generally speaking, it is on the medium soils, that is, site II, where the formation and maintenance of mixed pine and hardwood stands may be expected to succeed.

According to Cline and Lockard (p. 18), the composition of the natural reproduction in the cutover areas "varies with site, the character of the parent stand, as well as with the time and manner of its removal, and, perhaps most important of all, with accidental factors". Within a single stand, they noted (p. 18) "a wide variation in its composition even

TABLE 1

LINES OF DESCENT OF SITE AND SOILS CLASSIFICATIONS AT THE HARVARD FOREST, 1911–1952



over small areas", resulting in a grouping of individuals by species — a "groupwise distribution". They explained this groupwise distribution as follows (p. 26):

> Chiefly because of ground cover, soil factors, and large holes in the canopy of the parent stand, both the pine and the hardwoods are more or less concentrated in groups. The other condition is brought about by piling the slash in windrows, a common practice in logging. Necessarily, the restocking is largely confined to the lanes between the windrows, and a stripwise stand is started, although within the strip it tends to be groupwise.

The relation between composition of the volunteer reproduction and site variations was most clearly reflected in the hardwood component. The distribution of the white pine seedlings was believed to be little affected by characteristics of the site (p. 19):

> As to the pine element, its presence in the young stand is less influenced by site than by the supply of seed, for when old-field pine is clearcut in a seed year, pine reproduction usually follows, regardless of other factors. Pine is less exacting in its soil requirements than most of the better hardwoods, and may be found reproducing itself on light, sandy soils, as well as on the heaviest.

Most of the hardwood reproduction in the volunteer mixed stands resulted from the sprouting of trees present in the understory of the previous pine stands, and Cline and Lockard found that the composition was related to site differences (pp. 18–19):

> The species present as sprouts depend upon the composition of the advance growth, which in turn is largely influenced by site. On the best of the heavy soils, this consists of white ash, hard maple, beech, yellow and black birch, basswood, and elm, together with others which are more common on the medium soils, red oak, paper birch, black cherry, and red maple, and small amounts of those which are able to grow on the very light soils, white oak, poplar, gray birch, and pin cherry . . . . On site I, white ash is generally most abundant, with the maples and shade-tolerant birches (black and yellow) in second place. On the medium soils (site II) comparatively little ash is found as advance growth, red maple, red oak, and black cherry holding first place.

Density as well as composition was found to be affected by site variations (p. 19):

> Both the greatest variety in composition and the highest density of stocking are found on the most recently cut areas of site I. In other words, both the number of individuals and species of hardwood vary inversely with the

time since cutting, and directly with soil quality. On the lightest soils, only a scattering of such species as gray birch, white oak, and poplar will be present after cutting; whereas on the heavy soils there may be as many as 30,000 stems per acre and twenty different species.

The abundance of black cherry and, formerly, chestnut in the medium-aged pine stands led Cline and Lockard to comment on the theory of shade tolerance (p. 19):

> It cannot be said that the most shade-tolerant species are most abundant, or that they attain the largest size under the average old-field pine canopy . . . neither [black cherry nor chestnut] is as shade-tolerant as many of the others which are less numerous.

They discussed the changing composition of the advance growth during the life of the pine stand in terms of seed characteristics (p. 19):

> The light-seeded species in the advance growth are readily accounted for either by seed trees present in the stand itself, or around its margin. The heavy-seeded species, such as red and white oak, come in comparatively late, owing to the fact that the various animals which do most of the planting frequent chiefly the older pine stands.

From the starting point of a young volunteer stand of mixed white pine and hardwoods whose component species are concentrated in groups, Cline and Lockard (pp. 21–34) developed the idea of gradual destruction of groups of pines to the point at which single large pine trees occur scattered through a mature hardwood stand. The chief evidence consisted of a large number of height measurements of trees in the mixed stands, up to 70 years of age, that were growing on Sites I and II. The measurements showed (pp. 21–24, Figs. 4 and 5) that white pine was outgrown by every species of hardwood, both of seedling and sprout origin, during the first 15 years "with the exception of the very fastest-growing pine as compared with the slowest-growing hardwoods" (p. 24). Considering only the "dominant" or "free-to-grow" trees, Cline and Lockard (p. 28 and Fig. 7) found that

> . . . the poorest of the pine, if free to grow, equals in height the poorest of the hardwoods at about thirty-seven years; while the best of the pine does not catch up with the best of the hardwoods until sixty years of age. The best hardwood sprouts grow more rapidly than the best hardwoods from seed, up to an age of about sixty-two years; while the poorest, stunted seed hardwoods never equal in height the poorest sprouts.

They attributed the slow growth or death of the pines during the first fifteen to twenty years to some extent to root competition, but primarily to shade cast by the overtopping hardwoods. Then, "the period of death through shading grades off into a period of death through abrasion, although for a time the two forces work simultaneously" (p. 30). Cline and Lockard believed that the severity of abrasion depended upon site, density, and species composition, both of the latter two being directly affected by site. In brief, their reasoning was as follows. Good sites tend to produce trees that are tall in proportion to diameter. These are more subject to sway than stumpier trees and tend to abrade their neighbors more. This abrasion is accentuated by the higher densities that are characteristic of good sites. Hardwood species such as oak, beech, and basswood, characterized by Patton as "space-demanding", show a tendency to abrade pine crowns to a greater degree than such species as white ash, sugar maple, black cherry, red maple, black birch, yellow birch, and paper birch, which Patton characterized as "crowd-enduring". The distribution of these species is affected by site differences.

The actual conditions of the stands, presumably the result of these processes of attrition, was summarized by Cline and Lockard (p. 31) in terms of soil differences:

> Although the pine and hardwood elements tend to be groupwise in the beginning, groups of pine are rarely found in the older stands, particularly in high densities on site I. In understocked stands on the medium soils, many of the pines do survive, and in this case the groupwise form may be maintained until maturity. With high density and good soil, however, single pines are found growing on even terms with the hardwoods in old stands. In fact, the pine may be dominant in old stands. But this position of co-dominance, or dominance, was not achieved through the ability of the individual tree to withstand shading and abrasion by hardwoods throughout life. Rather it is due to the fact that the individual is a remnant of a group. Given at the start a group of pines, the hardwoods encroach farther and farther as the stand develops . . . starting at the outer edge, one rank after another of the pines is eliminated by the hardwoods until only a single pine remains. In the middle-age classes many of the pines eliminated are still standing, while in the old-age classes oftentimes only the prostrate stems, and stumps are found.

Soil characteristics also were believed to affect the size of the group of pines needed to secure a single pine survivor (p. 32):

> The size of the pine group necessary in order that there be a survivor is influenced by site and by the species of the surrounding hardwoods. On poorer soils, a smaller group will suffice to pull a single pine through than

is necessary on better soils; while with the space-demanding oak, the rate of reduction is much higher than with the crowd-enduring ash.

Further Modifications of Management Policy

The study of Cline and Lockard resulted in a further shift in the management policy at the Harvard Forest. In 1908, the management goal when cutting pure stands of white pine was the development of another pure stand of white pine. By 1918, the goal was changed to the development of a stand of mixed pine and hardwoods. By 1925, the goal became the creation of a mixed stand of pine and hardwood with the pines and the hardwoods segregated into groups within the stand (Cline and Lockard, Preface). Cline and Lockard suggested that a groupwise mixture of pine and hardwoods was feasible only on medium soils. Their management recommendations (pp. 37–48) represent the last comprehensive system for obtaining the natural regeneration of white pine that was proposed at the Harvard Forest. By the mid-1930's, the cutover areas located upon the upland till soils had almost all reverted to hardwood stands (Lutz and Cline, 1947).

The Concept of Soil Deterioration under Pure Stands of White Pine

During the mid-1920's when the regeneration of white pine at the Harvard Forest was becoming more and more difficult, attention was focused upon soil dynamics, particularly upon changes in the organic layers. This consideration led to comparative studies of soils, chiefly the organic layers, under pure pine and mixed hardwood stands. These studies were foreshadowed by ideas expressed by Fisher (1925, pp. 10–13) and Cline and Lockard (pp. 61–65).

First Statement of the Concept

According to Cline and Lockard (p. 62), "the first reason for the formation of mixed woods is that mixtures tend to conserve the fertility of the soil, while pure stands tend to dissipate it". This conclusion was based largely upon their interpretation of European forestry literature, fortified by the agricultural analogy of repeated planting of one crop on an area. They contrasted the German practice, common before the twentieth century, of growing a single species in even-aged stands with the French practice of growing mixed stands. In Germany, studies had shown a degeneration of the soil after several rotations of pure stands; whereas in France "for years the natural methods have been those more closely followed, and from that country little is heard about soil depletion, growth stagnation, and so on" (p. 62). According to Cline and Lockard, pure stands not only deplete soil fertility, but "pure forests, especially of conifers, tend to reduce the water content of the soil". As possible evidence of soil depletion in central New England, Cline and Lockard (pp. 64–65) offered a comparison between pure pine stands and mixed stands of pine and hardwoods:

> It has been observed locally in a great many cases that pure, even-aged pine stands slow up quite suddenly in growth when not more than sixty years old. They show a rapid rate of growth for thirty to forty years, and then a gradual slowing up until, at the age of about seventy-five, growth is practically nil. Possibly the chief reason for this is the lack of an understory of hardwoods and heavy-foliaged softwoods to protect the soil and to maintain its fertility. White pine grown in pure stands often has a "sickly" appearance. The bark looks dull in color, and the crown often lacks the blue-green color so characteristic of health. In stands not much over fifty years old, red rot (caused by *Trametes pini*) begins to make itself known, and so rapidly does it spread that stands seventy years old often show a loss in merchantable lumber of from ten to fifteen per cent. As regards quality, Tarbox [1924] has shown that better pine is grown with either hemlock or hardwood than in pure stands, and the results of the present study corroborate his findings.
>
> Mixed pine-hardwood stands give promise of maintaining their health and vigor for certainly well over a hundred years, thus making possible long rotations and the production of big timber of the highest quality. Old growth pine-hardwood mixtures two or three centuries old demonstrate the probability of such longevity, the pines having a firm, tight, bluish bark, and well-formed crowns with dark, rich foliage.

Fisher (1925) likewise drew a picture of the rapid decrease in the vigor and longevity of white pine after the settlement of central New England. He inserted the idea of steady soil improvement under the pre-settlement mixed forest (p. 8):

> . . . from the point of view of the soil it is plain that under such a continuous forest cover the tendency was all in the direction of improvement, and as regards the individual tree, especially the pines, there was a sustained vigor and longevity which little of the present second growth seems to promise.

Fisher retraced the origin of the pure stands of white pine, painting a gloomier picture than previously (1918a; Fisher and Terry). He believed (1925) that the better lands were cleared for agriculture, and that cuttings in the remaining woodlands were comparatively light for more than a century after settlement. Fisher visualized little degeneration of the forest from these cuttings (p. 9): "At the worst the result was far better than occurs to-day, since only the larger, better trees were cut and there was an abundance of young ones to take their places". The large-scale abandonment of farmland beginning about 1850 at first led to the development of old field white pine stands which were of high density, produced timber of fair quality, and were "almost without admixture with other species" (p. 10). However, in stands originating after 1880, "the amount and quality of white pine have steadily fallen off". Fisher believed that the cutting practices used after about 1850 led to a tremendous increase in numbers of the so-called weed species (gray birch, poplar, pin cherry) and hardwood stump sprouts, which "steadily eliminated the desirable elements in the forest" (p. 11), both old field and woodlot. He described the result as follows (p. 11):

> Trees which in respect either to form, age, or kind are merely weeds have multiplied a thousandfold. With sixty to seventy per cent of central New England now classifiable as woodland, almost the whole of our forest land is exactly in the condition of a garden that was never weeded.

Fisher thus concluded that the tendency of old field white pine stands to revert to hardwoods "of such desirable species as white ash, red oak, and sugar maple" (1925, p. 11) was thwarted in actuality. Noting the existence of "cases and sites where there may be for a time a possibility of the replacement of pine" (p. 12) Fisher concluded that

> . . . the effects of generations of neglectful treatment are too much for the slow-growing pine, and on all but the lighter soils, or in exceptional cases, the young crop is entirely shaded out. Beyond question, then — and this applies to all regions where hardwoods and softwoods occur together — cut-over forest land is reverting to hardwood progressively inferior both in kind and condition.

Fisher looked beyond the "superficial evidence" of the tendency of white pine woodlots to revert to hardwoods in a search for causative factors (pp. 12–13):

> . . . it begins to be obvious that other and more fundamental factors are also at work. It seems probable that under older stands of pure pine a definite deterioration of soil has taken place. In some cases this impoverishment may have carried over from the previous period of neglectful farming;

more often the slowing of growth on the part of the pine and the susceptibility to disease, both characteristic of the type, are probably to be connected with a progressive exhaustion of the soil. The form of such pine stands, particularly the shallow and rising crown canopy, allows considerable drying out of moisture and does not conduce to the building up of a beneficial humus layer. The exact nature of this alteration in the soil remains to be determined. That some unfavorable change occurs, the condition of the old stands seems plainly to indicate.

Reconnaissance Study

Fisher (1928) followed up the idea of soil depletion by studying the upper parts of soil profiles in an "approximately flat" area of about 7 acres. This area had supported an old field white pine stand, about 4 acres of which had been cut 18 years previously when the pine stand was 60 years old. The clear-cut area supported a mixed hardwood stand. The study area was a part of a tract where, according to Fisher (p. 8), the "general site conditions are nearly uniform". Fisher found that the soil under the pines contained "a distinctly podzolized horizon"; whereas 200 feet away under the young mixed hardwood stand the soil showed a "true mull profile". A diagram of the two kinds of profiles (Fisher, 1928, Fig. 1) shows the horizons in the upper 6 inches of the soil materials. Fisher (p. 9) described the soil under the pine stand as follows *:

> Beneath a thin layer of dry leaf litter [about 1 inch], chiefly pine and hemlock needles, is a deep zone of duff [duff, 1.5 inches; "humus," less than 1 inch; "soil-humus," less than 0.5 inches; total thickness about 2.5 inches], composed of raw humus, which merges into the characteristic leached layer [less than 1 inch]. Below this is a thin burnt sienna or enriched stratum [less than 0.5 inches] . . .

Underlying the "burnt sienna horizon" was a "yellow horizon" or "mineral soil zone". Under the young hardwood stand, the soil profile showed a trace of "organic horizon", underlain by more than 3 inches of "burnt sienna horizon", or "enriched" or "mull zone", in turn underlain by the "yellow horizon", or "mineral soil zone".

Fisher assumed that prior to the cutting operation the entire study area had possessed a soil profile like that found under the pine stand remnant. Thus he interpreted the differences in profiles as a recent development, and concluded that the podzol profile that characterized the pine stand was converted into a mull profile under the young hardwood stand within 18 years. He described this process as follows (p. 9):

* Depths in inches taken from Fisher's diagram.

> . . . both the heavy litter and organic layer that had accumulated in the previous stand, as well as the current annual leaf fall, have been almost completely decomposed and merged with the mineral soil to a maximum depth of five or six inches. The resulting brown earth closely resembles the best garden loam in porosity, color, uniformity of texture, and moisture content. So active is the decomposition of litter that less than one year's leaf fall remains on the ground, and even this is so thin as to expose the mineral soil over nearly 25 per cent of the surface.

Visualizing the humus cycle as a sort of revolving fund passing plant nutrients back and forth between trees and soil, Fisher viewed the layer of needle litter and duff present under the pine stand as a stoppage. He believed that the leached layer of the podzol profile constituted evidence that essential nutrients were locked up in the overlying organic layers, and concluded (p. 9): "With an organic layer decomposing very slowly and of such depth as to exclude all but the heaviest rainfalls, it is plain that the soil is in a static condition and without active fertility". Differences in the stands in the two soil areas were interpreted as further evidence of the detrimental effects of a deep organic layer. Not only were the pines in an unsatisfactory condition, but also the hardwoods in the advance growth, which were described as "stunted". Removal of the pine and the subsequent conversion of the duff produced a "dense and exceptionally thrifty" young hardwood stand. Discarding older concepts of suppression and availability of light, Fisher (p. 7) attributed these changes in the hardwoods to soil conversion:

> That this conversion of type has been accompanied by rapid and beneficial changes in soil condition has been abundantly evident, not only in the strong development of new vegetation following cuttings, but still more in the vigorous growth of the succeeding mixed stands.

The Harvard Forest policy of managing groups of pine within mixed pine and hardwood stands was fortified by results obtained in Fisher's study. He found (p. 10) that the soil under groups of pine as large as 2 rods in diameter was the same as under pure hardwoods at the end of a period of nineteen years after cutting. Fisher summarized the silvicultural implications of the soil changes (p. 10):

> In this experience with soil changes on the Harvard Forest, there is a lesson for silviculture. Podzolized soil, except possibly in northern regions where it may be unavoidable, indicates soil deterioration and relatively poor growing conditions. It develops commonly in pure white pine stands, which fall off in growth and health at comparatively short rotations. The

mull soil, on the other hand, is fertile and active. It develops rapidly in mixed stands, which have long been recognized, even by lumber operators, to produce the largest and best quality of softwood timber.

Detailed Examination of Soil Profiles

Fisher's reconnaissance study of organic horizons (1928) led to detailed field and laboratory studies of soils under old field pine stands, second growth hardwood stands, and mixed virgin forest (Griffith, Hartwell, and Shaw, 1930). The main purpose of the study was to trace the changes in the upper parts of the soil materials over a 160 year period — representing 80 years of old field white pine and 80 years of succeeding hardwoods — substituting space for time. Thus, they examined soil profiles in old field pine stands ranging in age from 10 to 80 years, and profiles in second growth hardwood stands ranging in age from 5 to 40 years. Lacking proof that any hardwood stands over 40 years of age had followed the cutting of old field pine, they turned to culled woodlots for information concerning the older hardwood stands. In addition, soil profiles were studied in a tract of virgin forest, which was believed to represent "conditions formerly obtaining in the climax forest on the areas where the contrasted pine and hardwood plots were located" (p. 19).

ASSUMPTIONS

Griffith, Hartwell, and Shaw approached the study of soil materials from the point of view of the pedologist. In other words, they turned to the concept of the soil as a natural body that is distinct from the underlying geological materials. This concept had been championed in the United States chiefly by Marbut, who drew heavily upon European soil science. Griffith, Hartwell, and Shaw (p. 13) clearly stated their assumption of climatic and vegetational control of soil development: "Since the soil profile is the direct result of all the influences of climate, it varies extensively in different regions and under varying cover types". Fisher (1930, pp. 7–8), in his introduction to their report, elaborated this idea:

> The accepted theory of soil origin, which is in effect that similar types of soil are the product of similar climates, makes it important to know how far and in what directions the unstable phases of forest vegetation, which have now so largely replaced the original forest, affect the profiles climatically characteristic of the region.
>
> It is plain that if climatic factors are primarily responsible for differing types of soil, we should expect modifications to follow the varying influence of forest cover upon temperature, moisture, and radiation. As between

forests which are largely evergreen and those which are deciduous, there is obviously on the forest floor a wide variation in seasonal temperatures, in the amount and penetration of rainfall, and in the intensity and duration of light. Any particular combination of these factors must also be limited in its effect upon soil metabolism by the character of the forest litter, the relative toughness, consistency, and perhaps chemical content of the leaves. Both these influences in turn affect the microflora and soil fauna, which play a part in the derivation of plant food. Thus we should expect that, on sites of similar topography and elevation, pronounced variation in forest composition of sufficiently long duration would result in corresponding changes of soil profile, especially in the depth, condition, and rate of decomposition in the humus layers.

It is interesting to note that the climatic theory of soil development was not emphasized by Latimer, Martin, and Lanphear (1927) in their description of the soils of Worcester County. Rather, they viewed the soils as slightly modified glacial deposits (pp. 1544–1545, 1547):

> The soils of the county, even those with the most perfectly developed characteristics, are marked by incompletely developed profiles. This means that the soil-forming processes have not yet effected any profound change in the soil material, and that the soil is not widely different from the materials when they accumulated. . . .
>
> One reason for the simplicity of the profiles of the Worcester County soils, in that they seem to possess almost the same features as regards eluviation as the original material when it was first accumulated by the ice, is the short time during which the soil-developing processes have been at work, the deposition having taken place during the latter part of the glacial period. . . .
>
> The soils of Worcester County, therefore, are young, because the changes which have taken place in them since the accumulation of the parent glacial material are comparatively slight. About the only changes that have taken place are the accumulation of some organic matter and the assumption of a brown color which is due partly to some oxidation of the iron in the soil minerals and partly to the organic matter.

This paper was available to Griffith, Hartwell, and Shaw, and indeed these very quotations are paraphrased in their report (p. 16).

Fisher's introduction to the report of Griffith, Hartwell, and Shaw is invaluable in that it discusses at length the assumptions underlying the study. Thus from the initial assumption of climatic control of soil development, and the belief that soils within a single climatic regime at similar altitudes and in similar topographic positions would closely reflect variations in the composition of the vegetation, particularly in the humus layers, Fisher concluded that "the rate of decomposition of the humus layers is a fair index of soil fertility" (p. 9).

However, this developmental approach based upon a characterization of soil materials from the surface downward required that the surficial deposits below the level of the B horizons be uniform in all areas studied. Fisher (1928) had assumed lateral uniformity in an area of about 7 acres. Griffith, Hartwell, and Shaw expanded this assumption of uniformity to include a much larger area in the town of Petersham. Although they assumed that "the original soils and climate are substantially uniform for the locality" (p. 16), they selected plots on the basis of a reconnaissance soils map of Worcester County (Latimer, Martin, and Lanphear). All plots were located on soils belonging to the Charlton, Gloucester, or Brookfield series. The following brief descriptions of these soil series are from Latimer, Martin, and Lanphear (pp. 1549–1550):

> The soils of the Gloucester series have brown surface soils and yellowish-brown to yellow subsoils which grade downward into gray unweathered till. The subsoils are usually of the same or lighter texture than the surface soils. Gloucester soils represent comparatively shallow deposits of glacial till derived mainly from gray granites and gneisses, and which contain more or less rounded rocks and boulders. . . .
>
> The soils of the Charlton series have rusty-brown surface soils, and mellow, ocherous-yellow subsoils, greenish-yellow lower subsoils, and greenish-gray substrata. The geological deposits are fairly deep in all cases except the stony types, and in places they are ledgy. Charlton soils are derived from quartz schist, quartzite, and white granite, and are comparatively free from stone, except the stony types, which contain fragments and slabs of schist and some rounded granite stones. The subsoils and substrata are heavier than those of the Gloucester soils. . . .
>
> The soils of the Brookfield series have dark-brown to rusty-brown or reddish-brown surface soils and ocherous-yellow to rusty yellowish-brown or reddish-brown mellow subsoil materials which become only slightly paler in the deeper subsoils and substrata. The lower subsoils are only slightly lighter in texture than the surface soils and upper subsoils. These soils represent rather shallow glacial till derived from a rusty-brown schist (Brimfield schist) which contains a quantity of iron pyrites which imparts the peculiar ocherous color so characteristic of these soils.

The three soil series, though differing in many characteristics and derived from different kinds of materials were lumped by Griffith, Hartwell, and Shaw (p. 17):

> These three series proved on analysis to be sufficiently alike so that the plots on them were considered comparable and averaged together. According to Dr. Lanphear, who accompanied the party on an early field trip, profile studies on all three could safely be combined.

Fisher (1930, p. 10) believed that the land-use history provided another line of evidence for lateral uniformity of the soil: "A century of tillage and grazing has obliterated all trace . . . of the original soil profile. . . ."

Application of the concept of climatic and vegetational control over soil development within a small area over an extremely short time span can create more problems than it solves. Applied to an interpretation of soil fertility stated in terms of variations in the gross characteristics of humus layers, the concept requires a further assumption, the random distribution of species. Workers at the Harvard Forest recognized that leaves of different species possess different physical and chemical properties that might affect the microbiological processes active in the soil and thus the nature of the humus. If variations in the soils determined the distribution of species to any appreciable extent, variations in species composition would be an effect of soil differences, not a cause. Then the belief in the lateral uniformity of the well drained till soils would become untenable, and variations in fertility could not be attributed solely to differences in the humus layers. Fisher argued (1930) that the composition of the wild stands that grew up in the abandoned fields was entirely the result of random dispersal of seed by wind, rodents, and birds. As for the origin of the old field pine stands, he stated (p. 10):

> Because of the comparative abundance and superior effectiveness of pine seed trees during the period of most extensive farm abandonment and the corresponding scarcity of the inferior, light-seeded hardwoods, which have since reached such abundance, most of the older pine stands are substantially pure. . . .

He believed that the local distribution of hardwoods of various species within the old field pine stands was accidental, as was also the distribution of the seed trees from which these hardwoods were derived (p. 11):

> It is significant that this secondary phase of hardwood is thoroughly accidental as to its distribution. A brief examination of an old field pine forest will reveal distinct groups or patches of young hardwoods, sometimes as large as half an acre, in each of which one or more species may greatly predominate. In almost every case the origin may be traced either to neglected fence corner trees or to scattered old hardwoods in the pine stand, identifiable as specimens surviving from the previous era of farm and

pasture. Just which species may have been on hand to furnish seed, either during or after the pine phase, is plainly a matter of accident.

FIELD RESULTS

Griffith, Hartwell, and Shaw followed Fisher's classification of soils (1928) and recognized two kinds of profiles, podzol and mull. Horizons in the podzol profiles were designated according to the system proposed by Glinka (1927), and the same names and symbols were used in describing mull profiles "for layers homologous to those in the podzol" (Griffith, Hartwell, and Shaw, p. 16). Organic horizons were separated on the basis of degree of decomposition, and mineral horizons on the basis of color. In general, the soil materials were examined down to the C horizon *, which was found at an average depth of 20 inches in 105 measurements. At each plot profiles were exposed in a face at least 6 inches wide by means of a machete. The C horizon was examined by means of a soil auger, but because of "the prevalence of rocks and boulders in many of the plots, it was impossible to reach this horizon" (pp. 19–20).

Primary emphasis was placed upon the thickness and nature of the organic layers and the thickness of the "dark brown zone" or "B_1" horizon. These data were derived from 187 profiles in 62 old field white pine plots and 185 profiles in 62 hardwood plots, and organized into ten-year age classes. From these data, Griffith, Hartwell, and Shaw drew the following conclusions (pp. 20–27). In the old field pine stands, litter

TABLE 2

LEACHED HORIZONS (A_2) IN SOIL PROFILES UNDER OLD FIELD PINE STANDS (FROM TABLE I, GRIFFITH, HARTWELL AND SHAW, 1930)

Thickness in Inches	*Age of Stand*							
	10	20	30	40	50	60	70	80
0.6–0.4	–	–	–	–	1	–	–	2
0.4–0.2	–	–	–	–	–	–	–	–
0.2–0.1	–	–	–	–	–	6	–	1
0.1–0.05	–	–	1	4	10	16	–	3
0.0	12	21	38	20	28	16	9	4
Percentage of Profiles Showing a Leached Horizon	0	0	2.6	16.7	28.2	57.9	0	60.0

* As defined by Griffith, Hartwell, and Shaw (p. 15) a mineral horizon "composed of weathered material which has not been enriched by deposition from the horizons above it".

(A_o^1), duff (A_o^2), and humus (A_o^3 and A_1) zones increased over the 80-year period to a thickness of less than 2 inches. Beginning with the 50-year age class, "leached zones" (A_2) sometimes were observed (Table 2); but the average thickness of this horizon was never as much as 0.3 inches in the 80-year period. One profile in the 50-year age class was described as having "a well defined leached layer" (p. 23), and was between 0.4 and 0.6 inches thick. The average thickness of the "dark brown zone" (B_1) was 9 inches in the youngest pine stands (10-year age class). This was "about the depth of the old culture horizon" (p. 20) or plow layer in the cultivated fields upon which the stands presumably had become established. They found that this dark brown zone became steadily reduced in thickness; and after 80 years of pine occupancy, it showed an average thickness of less than 1.5 inches (Table 3).

In the hardwood stands, "most of the current hardwood litter decomposes annually, and the entire organic horizon is less than an inch deep" (p. 23) from the tenth to the eightieth year. The pine litter that, presumably, was present disappeared during the first ten years of occupancy by hardwoods. The dark brown zone fluctuated widely during the eighty year period, ranging in thickness from 2 to about 13 inches.

Other field observations included comparisons of tilth, ground cover, earthworm activity, and characteristics of root systems. Tilth, or the physical properties of soil that result from the combined characteristics of consistence, structure, and flocculation of colloids, was found to be a function of the forest cover and subject to conversion within one rotation. Thus, the "poor tilth" found under 80-year-old pine stands, characterized by a compacted dark brown zone having granular or columnar structure and little flocculation, changed to "good tilth" under the hardwoods, where the dark brown zones were characterized as friable, generally well flocculated, and possessing crumb structure. The ground cover in both pine and hardwood stands consisted largely of the same species, although the number of individual plants was much higher under the hardwoods. According to Griffith, Hartwell and Shaw, "The occurrence of the same species on widely different profiles may be explained by the fact that the soil reaction under both types of forest is very similar" (p. 31). Earthworms generally were found in the hardwood stands, but were found in only one young pine stand. They occurred in soils having high acidity (pH 3.8 to 5.4) and "were always associated with soils having good tilth" (p. 32). The "feeding roots" of pines were concentrated in the upper parts of the profile, in contrast to those of the hardwoods, which showed more diffuse root systems. Griffith, Hartwell, and Shaw suggested that "this concentration of the feeding roots is probably due to

TABLE 3

THICKNESS OF DARK BROWN HORIZONS (B_1) UNDER SECOND GROWTH PINE AND HARDWOODS (FROM TABLES 1 AND 2, GRIFFITH, HARTWELL, AND SHAW, 1930)

	Thickness in Inches							
Age of Stand	up to 10	20	30	40	50	60	70	80
Pine								
Range	4 to 14	3 to 11	1 to 13	1 to 9	0 to 7	1 to 7	0 to 5	0 to 6
Approximate mean	9.0	6.0	6.5	3.5	3.0	2.5	1.5	1.25
Hardwood								
Range	2 to 10	0 to 18	0.1 to 7.0	1 to 4.5	–	8 to 11.5*	2 to 20*	1.2 to 9.0*
Approximate mean	4.5	3.5	3.0	4.0	–	8.0	7.0	6.0

* culled woodlots

the larger abundance of available nitrogen in the surface layers of the pine profiles" (p. 32).

Most of the report relates the results of laboratory analyses of the different horizons. It includes the most detailed studies ever made at the Harvard Forest on the chemical properties of its soils. Texture, organic content, hydrogen-ion concentration, buffer content, and nitrogen content were determined for a varying number of profiles, including the dark brown zone (B_1), the light brown zone (B_2), and the unenriched zone (C).

Soils in the Pisgah Forest, a so-called virgin forest in southern New Hampshire *, were also examined by these authors (pp. 69–74). They believed (p. 69) that the soil profiles in the Pisgah Forest represented "not only conditions preceding the farming area and the subsequent development of the transition types considered in this study, but also conditions to which the present types (if undisturbed) would in time revert".

Griffith, Hartwell, and Shaw recognized four forest types within the Pisgah tract, and studied soil profiles within each of these types. Table 4

TABLE 4

MEAN THICKNESS IN INCHES OF SOIL HORIZONS IN PROFILES WITHIN THE PISGAH FOREST

(ADAPTED FROM GRIFFITH, HARTWELL, AND SHAW, 1930)

Horizon	*White Pine-Hemlock* (*54 Profiles*)	*Spruce-Hemlock* (*6 Profiles*)	*Pure Hemlock* (*3 Profiles*)	*Mixed Hardwoods* (*41 Profiles*)
litter	0.5	0.7	0.5	0.1
duff	1.3	1.1	1.3	0.7
humus	1.6	3.6	2.5	0.9
leached	1.3	2.1	1.4	0.8
dark brown	1.1	2.0	1.6	0.4

shows their measurements in terms of mean horizon thickness within the types. Note the similarity of the profiles, and the presence of a leached layer under the "mixed hardwoods type" that is much thicker than any leached layer found at the Harvard Forest under the old field white pine stands. According to their report (p. 70), "the explanation [of the leached layer under the mixed hardwoods] may be the overlapping phases of succession, the stagnation of the whole physiology of over-mature forests, and the infrequency of the more soil-improving

* For description of the Pisgah Forest, see Cline and Spurr (1942).

species". Note also that the dark brown layer is much thinner under mixed hardwoods than under the other types.

The field sheets for the study show that the thickness of the leached layers ranged from 0 to 2.6 inches in the "mixed hardwood type" and from 0.5 to 6.0 inches in the "pine-hemlock type". However, the dark brown horizons ranged in thickness from 0 to 3.0 inches in the hardwood type, and from 0 to 5.0 inches in the pine type. The pine plot that showed the thickest leached layer had a dark brown horizon of 4.5 inches. The thickness of the dark brown horizons varied widely among the three profiles examined at each plot. At least one profile in about three-fourths of the hardwood plots showed no dark brown horizon or only a trace, but this condition was observed in only about one-fourth of the pine plots.

INTERPRETATION OF FIELD DATA

Griffith, Hartwell, and Shaw purport to describe soil evolution from podzol to mull profiles accompanying changes in forest composition from predominately white pine to predominantly hardwood. As one criterion for the recognition of a podzol profile they (p. 13) used the presence of a leached layer (A_2 horizon):

> The podsol profile is characterized by a thick mantle of litter and humus underlain by a zone of leaching, gray in color, from which organic matter and colloids have been washed down and redeposited in the enriched horizon beneath it. The mull profile is characterized by the absence of the leached zone and by marked structural differences.

In the second growth stands examined, leached layers occurred sporadically under old field white pine stands more than 20 years old (Table 2), but never attained a thickness of more than 0.6 inches. Of the profiles that showed leached layers, 93 percent were only 0.2 inches or less in thickness. Nevertheless, none of the second growth hardwoods that followed pine stands possessed leached layers. These data may indicate a trend toward formation of podzol profiles under pine, but at present the so-called "podzol profile" probably would be classified as micropodzols overlying brown podzolic soils. In current soils classification, the "mull profile" becomes a soil belonging to the Brown Podzolic great soil group or zonal soil. In the Pisgah Forest, leached layers were found in soils supporting all forest types. Nevertheless, leached layers were more commonly found under the pine-hemlock type, and the thickest leached layer was found under the pine type.

Griffith, Hartwell, and Shaw attributed the wide fluctuation in thickness of the dark brown horizon under the hardwood stands (Table 3) to variations in species composition (pp. 23–24):

> In order to bring out any relationship between this fluctuation and the composition of the prevailing leaf litter, the plots were thrown into three classes . . . based upon susceptibility of the leaves to decomposition, as shown by the results of type conversions on the Harvard Forest . . . plots, which contain a preponderance of white ash, elm, basswood, white birch, and yellow birch, usually have a deeper dark brown zone than . . . plots, containing a preponderance of hornbeam, pin cherry, black cherry, aspen, black birch, soft maple, and hard maple . . . [which in turn] generally have deeper dark brown zones than . . . plots containing a preponderance of red oak, white oak, beech, white pine, and chestnut.

The evolution of B horizons in response to changes in the vegetative cover was questioned at the Soils and Forest Conference held at the Harvard Forest in 1939:

> The pronounced soil transformations as described from Petersham were questioned. The soils specialists believed that the deeper B horizons observed in the mosaic of shallower and deeper locales under hardwoods had been present under previous stands of pine with podzolising tendencies. The Harvard Forest interpretation had been based on the belief in shallower B horizons under pine from evidence of simultaneous measurements on soils under stands of various ages. The need for periodic observation of given areas [was] evidenced by conflict of opinion.

Griffith, Hartwell, and Shaw briefly considered and then discarded the possibility of variation in the B horizons that was independent of the second growth stands. Though they argued for uniformity on the grounds of one pedological and two botanical assumptions (p. 26), adoption of a field method in which space was substituted for time immediately required the assumption of vegetational control over the development of B horizons:

> These relations of composition to the depth of the dark brown horizon are not without significance. It may be argued that the more exacting species would naturally be found on the better soils, but the old field background precludes this possibility. The distribution of hardwood species on cutover pine lands is largely accidental, and is plainly governed by the occurrence of sporadic seed trees in the previous pine or fence corner survivals from the old fields (Patton, 1922). Furthermore, the period since the old field condition is too short for the effect of site factors upon distribution to assert itself. It seems plain, therefore, that in stands under eighty years old, the various species help to develop and maintain the soil conditions

> with which foresters usually associate them. In the present case the differing effect of the several groups . . . [of species] gains additional significance from the fact that all have originated on a similar and degraded soil.

In the Pisgah Forest, however, the mean thickness of the dark brown horizons in the "mixed hardwoods type" was only about one-third that found in the "white pine-hemlock type" (Table 4). Furthermore, this horizon reached its maximum thickness under the pine, and was more often present under the pine type.

The pronounced differences in soil profiles found under similar forest types in virgin and second growth forests were discussed by Griffith, Hartwell, and Shaw (p. 73):

> In general, these profiles indicate that the favorable and unfavorable influences which appear so clearly segregated in the studies of second growth stands are, to a considerable extent, merged and obscured in the virgin forest. The apparent discrepancy between the profiles under the younger hardwood stands succeeding old field pine and those examined under the hardwood phases of virgin forest is probably to be explained . . . in terms of differing life history and composition.

They pointed out that in the second growth hardwood stands an initial period of "exposure" following the cutting of the pine was followed by the development of a "rapidly changing" herbaceous and shrubby vegetation and development of a "comparatively low and shallow" (p. 73) leaf canopy. According to the writers, these features — absent from the virgin forest which had experienced "no recent nor wholesale exposure of the ground" (p. 74) — strongly affected temperatures and radiation, and thus the microclimate of the forest floor. Furthermore (p. 74),

> The forest canopy at Pisgah has developed to a far greater depth, and there is commonly a large accumulation of subordinate elements in the stand, underbrush, suppressed and intermediate trees, together with the apparent tendency over long periods toward alternation of hardwood and softwood dominance.

Griffith, Hartwell, and Shaw then proceeded to the inexorable conclusion that even mixed hardwood stands were "bad" for soil development (p. 74):

> These conditions would certainly have a tendency to offset the more favorable influence of hardwood associations as compared with those of softwood on soil metabolism. In fact, even in second growth hardwood stands those which have reached an age of eighty years or more and in which no cutting has occurred often show a slowing down of decomposi-

tion in the humus layers and consequent accumulation of organic material, which suggests progress toward the profiles characteristic of the virgin forest. It would appear that even the most favorable influences of forest composition upon soils must be to some extent regulated by periodic cuttings and suitable rotations.

Discussion

For several reasons, an inordinate amount of space has been devoted to the concept of soil deterioration under pure stands of white pine. First of all, the belief in soil deterioration led to the first intensive studies of site at the Harvard Forest, not just in terms of growth rates of the trees, but in terms of the soil materials themselves. These studies culminated in laboratory analysis of the physical and chemical properties of various parts of the soil profile.

Secondly, the series of studies provide a not-too-happy example of the deductive method as applied to field studies in natural science. Turning to European experience in forestry for the second time, the Harvard Forest personnel adopted as a general principle the belief that pure stands of conifers deplete soils. Observing thick layers of organic matter under old field white pine stands, and the absence of similar layers under hardwood stands, they assumed that the organic matter represented a stoppage in the nutrient cycle. Turning next to a study of soil profiles in a small, partially cutover pine stand, Fisher (1928) found that these differences in humus layers were related to differences in the deeper soil horizons as well as to differences in the vegetative cover. By assuming that the whole profile, not merely the humus layers, present under the pine remnant formerly had extended throughout the entire area, he was able to conclude that cutting the pure pine had converted a podzol profile into a mull profile within a period of eighteen years.

The obvious next step was to determine whether these changes in soil profiles generally accompanied a change in the forest cover. For many years people at the Harvard Forest had successfully used the method of substituting space for time in studying tree growth and stand development. It was therefore perhaps a natural thing to apply the method to a study of soil changes. However, soil materials differ in at least one important characteristic from trees. All but the surface is invisible to the observer, and machetes and soil augers only partially reveal the nature of the surficial deposits. Thus the field method adopted by Griffith, Hartwell, and Shaw immediately required the assumption of uniformity within the deeper parts of the soil materials. To justify this assumption, they turned to the theory of climatic and vegetational control over soil development, and they emphasized the old field background of most of the areas examined. In addition, they lumped mapped variations in the soil materials which were based upon known differences in the deeper horizons. The assumption of uniformity, in turn, led to the further assumption of accidental distribution of species. Carried to its logical endpoint, this framework of assumptions led to the statement that in forests up to eighty years of age, the trees themselves produce the soil conditions that foresters associate with the different forest types. This conclusion leads inevitably to the elimination of soil materials from a consideration of the relations between a forest and its environment. At the base of the field method was an unwarranted belief that the deeper parts of the soil profile could be ignored, or considered to be uniform.

Fisher (1930, pp. 11–12) summarized the series of interlocking assumptions:

> The chronology of the whole succession to which the present observations apply may be summed up as follows: an indeterminate past of mixed virgin forest, a hundred years of pasture and tillage, eighty years of pure white pine, and forty years of mixed hardwood. We have thus today two sharply distinct phases of forest composition, accidentally segregated by the circumstance of land history, beginning on bare land of uniform original soils with no distinct humus layers, developing in turn on the same areas, and occurring without relation to the original effect of local site factors upon distribution. With this fortunate elimination of variables, it may be concluded that the principal contrasts to be found in the evolution of the humus layers and contiguous dark brown zones under old field pine and succeeding hardwood may be traced to the influences of these contrasting phases of composition.

Thirdly, the idea of soil deterioration itself is an interesting phase in the history of the Harvard Forest. One wonders what aroused these apprehensions in 1925, when only seventeen years earlier similar pine stands were promising enough to form a basis for sustained yield management. It seems unlikely that the old field white pine stands cut in 1908–09 were less weeviled, less damaged by red rot, or of better form and quality than those of 1925, which were described in rather gloomy terms by Cline and Lockard (see p. 63). Undoubtedly, the Harvard Forest staff hoped to improve the quality of new stands of pine by management; but the mature, unmanaged stands certainly were not without value. Perhaps the boxboard market for poor quality pine was showing signs of faltering. Its actual collapse was imminent. Nevertheless, one gets the impression that podzols and thick organic layers were being charged rather unreasonably for a general failure to regenerate the pine stands.

The climax of the period of preoccupation with soil deterioration was the paper of Griffith, Hartwell, and Shaw. Their study provided invaluable information pertaining to the physical and chemical properties of the upper parts of the surficial deposits (much of their raw data was published), and paved the way for studies of the soil materials as a whole. In addition, the emphasis upon surface organic matter led to a detailed study of the relations between earthworms and variations in the composition of the forest litter (Johnston, 1936).

Nevertheless, from the point of view of site evaluation, or the prediction of composition and production rates of the forest crop, the series of studies ended in a cul-de-sac. Furthermore, the evidence presented to show soil evolution under a succession of forest crops is highly equivocal for all parts of the profile except the organic horizons.

First Comprehensive Plan for the Management of Volunteer Mixed Hardwood Stands

The last extensive analysis of volunteer unmanaged stands that had followed the cutting of old field white pine was made by McKinnon, Hyde, and Cline (1935), who examined 225 stands in a 1500 square mile area in central New England. This work followed in the footsteps of studies by Fisher (1918b), Terry (1918), Fisher and Terry (1920), Averill, Averill, and Stevens (1923), and Cline and Lockard (1925). But, unlike the earlier studies, this one extended far enough to the southward to include the so-called central hardwood region of New England forestry usage.

As other studies had shown, McKinnon, Hyde, and Cline found that old field white pine stands were almost always followed by hardwood stands: "In 83 per cent of the cases pine has been completely replaced by hardwoods, and in the remaining 17 per cent, comprising those lots cut in pine seed years, it will form only a minor portion of the final stand" (p. 67). Thus their study largely constituted a survey of hardwood stands to determine "the silvicultural condition of these stands and their susceptibility to profitable treatment, as influenced by the various factors of age, soil, and stand history" (p. 7).

The 225 stands, ranging up to 45 years old, were grouped into three regional types according to composition: 1) northern hardwoods type (12 stands), characterized by a high proportion of paper birch, beech, and sugar maple; 2) oak type (15 stands), characterized by a high proportion of red, scarlet, and white oak; 3) transition hardwoods type (198 stands), "situated chiefly in the central part of the area covered and evidently transitional in their make-up" (p. 29). Most of the paper is concerned with stands classed as transition hardwoods.

The trees constituting the stands were divided into crop trees, weeds, and trainers. Crop trees consisted of potential sawtimber trees of the following species: red oak, white ash, paper birch, beech, white oak, scarlet oak, hickory, white pine, hemlock, and red spruce. Weeds consisted of gray birch, pin cherry, poplar, and red maple trees, as well as single-stemmed and multiple-stemmed sprouts from large stumps of almost all hardwood species. Trainers consisted of understory trees of all species.

The sites supporting the 225 stands were classified according to tree height into three categories (ftn. p. 24):

> Site III for pine is a very poor site for hardwoods, and local yield tables for hardwoods include only Sites I and II. Using height at age 50 as an index to site, Site I for even-aged, mixed hardwoods is indicated when the height of dominants and codominants ranges between 65 and 75 feet; Site II, between 55 and 65 feet.

This classification of site by height of the trees was further related to characteristics of the soil materials (p. 24):

> . . . Site I included the most favorable situations with moist, dark colored soils, high in humus content, of mull structure, and located chiefly on the lower slopes; Site II, a broader division including the moderately fertile situations with somewhat drier and less humus-rich soils, though also exhibiting the mull structure, and usually found on the upper slopes and ridge tops; and Site III, a comparatively uncommon site for the region covered, including the least favorable situations with dry, sandy or gravelly soils, light in color and coarse in texture, occurring chiefly in the valleys.

However, this classification was modified to fit conditions (see Table 1) within the study area (pp. 24–25):

> Because of the very limited number of cut-over lots found on Site I, samples taken on this site were grouped together with those on Site II under the designation "Site II and Better." This is comparable with the terms "better sites" and "heavy soils" frequently used in other Harvard Forest publications. Secondly, as the field work progressed, it was decided to set up a new site, intermediate between Site II and Better and Site III, to be designated as "Site II Minus." This was considered necessary in order to provide for the comparatively dry and exposed upland situations commonly found in the southern part of the region studied, sites occupied

chiefly by oaks, chestnut, and hickory, plainly poorer than Site II but not so dry and sterile as Site III.

This modified site classification was also related to the nature of the soil materials. Thus, Site II and Better was equated with medium to heavy soils (p. 67), Site II Minus with light to medium soils (p. 74), and Site III with very light soils (p. 75).

According to McKinnon, Hyde, and Cline (pp. 58–61), most of the stands that followed the cutting of the pine stands in a seed year contained some white pine; and the percentage of free-to-grow pines varied with site. Thus, on Site II and Better the number of free-to-grow pines dropped sharply between the tenth and fifteenth year after cutting, and pines generally were lacking from stands more than 30 years old. On Site II Minus, free-to-grow pines were present in fifteen-year-old stands, which "indicates that suppression proceeds at a slower rate on the poorer soil" (p. 61). Free-to-grow pines were present in all stands growing on Site III.

In the transition hardwood type, McKinnon, Hyde, and Cline found that many of the characteristics of the stands were related to variations in site as defined by the three site classes.

The density of stocking was highest on Site II and Better, lowest on Site III, and intermediate on Site II Minus. This differential was reflected in the number of crop trees. On Site II and Better, the number of crop trees per acre ranged from a maximum of 750 to 1000 in stands less than 10 years old, to a minimum of 100 to 200 at age 45. The number of crop trees per acre on Site II Minus ranged from a maximum of 200 to 550 in stands less than 10 years old to a minimum of 100 to 150 at 30 years. On Site III, the stocking of crop trees generally was less than on Site II Minus, especially in the younger stands.

Form and quality of the crop trees, "judged on the basis of the general appearance of the trees, particularly the straightness and clearness of their boles" (p. 27), were highest on Site II and Better, lowest on Site III, and intermediate on Site II Minus.

McKinnon, Hyde, and Cline (pp. 41–57) showed that the species composition of the crop trees, the weeds, and the trainers in the transition hardwoods, as well as the numbers of individuals of a single species, varied with differences in site. The composition of the crop trees will serve to illustrate the nature of this variation. In number of individual trees, red oak led all species on all three sites. White ash, as abundant as red oak on Site II and Better during the first five years, decreased rapidly in numbers. White ash was less common on Site II Minus and "very poorly represented" on Site III. Paper birch, black birch, and sugar maple were common on Site II and Better, less common on Site II Minus, and rare on Site III. Yellow birch, common on Site II and Better, was rare on Site II Minus, and absent from Site III. Beech was rare on Site II and Better and absent from the poorer sites. White oak and scarlet oak were rare on Site II and Better, more abundant on Site II Minus, and most abundant on Site III. Hickory, rare on Site II and Better, was more abundant on Site II Minus, but absent from Site III. Hemlock was absent from Site III.

A similar composition differential appeared in the tally of hardwood stumps and hardwood "residuals" that grew in the preceding pine stands (pp. 33–36). In explaining the distribution of crop trees within a stand, the authors (pp. 34–36) used Fisher's hypothesis of chance distribution of species and noted a close relation between the distribution of trees in the previous stand and trees of the same species in the reproduction.

The management recommendations of McKinnon, Hyde, and Cline (pp. 67–77) for the volunteer stands were based upon the assumption that high quality hardwood sawtimber was the most desirable crop. They believed that this goal could be attained in stands of the northern hardwood type, but that in stands of the oak type the sawtimber would be of relatively low quality. In stands of the transition hardwoods type, they believed that high quality hardwood sawtimber could be attained on Site II and Better, somewhat lesser quality sawtimber on Site II Minus, but no sawtimber at all on Site III unless pine reproduction was present in quantities. Thus site evaluation allowed not only the prediction of the species composition of the crop trees but, perhaps more important, site evaluation would be of assistance in making decisions as to the intensity of management in young stands. Site evaluation loomed large in their recommendations because the authors proposed a high intensity of management.

In stands believed capable of producing quality sawtimber, they viewed the problem as one of maintaining a high number of potential crop trees in the younger age classes from which final crop trees might be selected, along with sufficient trainers to insure good form and quality. Thus they strongly advocated weedings between the ages of 5 and 15 years to eliminate weed species and the multiple-stemmed sprouts (p. 70):

> Although the time for the most effective control of weeds is between five and fifteen years, stands which have recently attained cordwood size are still within the limits of profitable treatment. . . . Improvement and release cuttings, to be most effective and well within the range of profitableness, should be undertaken before the stand is thirty years old.

Nevertheless, ". . . in the oldest stands studied, 45 years, there is an average of nearly 150 free-to-grow crop trees per acre and the number of overtopped crop trees is practically nil." And further (p. 71), "The finding that, in spite of 45 years of unregulated competition, about 150 crop trees per acre have succeeded in holding or gaining a dominant position in the stand, should be a source of encouragement to owners of cutover pine land and a strong argument against clearcutting middle-aged stands for cordwood." In short, they showed that no management at all resulted in fully stocked stands of crop trees in stands up to 45 years old. Therefore, management decisions would seem to hang entirely upon a rigorous economic analysis.

Disaster: The Hurricane of September, 1938

Although the 1930's revealed that most of the attempts to regenerate white pine on the cutover lands in the Harvard Forest had failed, a considerable amount of old field white pine had yet to be harvested. In a sense, the woods operations were slightly schizophrenic, with cutting proceeding according to the initial plan of sustained yield management of white pine, while treatments in the young stands were aimed largely toward improving the quality of the young hardwood trees. On September 21, 1938, a devastating tropical hurricane (Brooks, 1940) destroyed almost all of the merchantable white pine remaining in the Harvard Forest and, after a two-year period of salvage operations, the Harvard Forest staff faced a simplified management problem. As put by Merrill (1947, p. 5): "Thus it was that a natural phenomenon emphasized the end of a thirty-year period in no uncertain manner".

The damage to the Harvard Forest has been briefly described by Merrill (p. 5):

> At least two-thirds of the merchantable sawtimber on the Harvard Forest holdings were completely uprooted or left as broken stubs. It is here recorded that from the fallen trees, within the following two-year period, about 6,500,000 board feet of lumber were salvaged and sold, the equivalent of the allowable annual cuts of nearly fifteen years, and about 2,000 cords of fire wood. Thus it was that many years of lumbering operations were telescoped into a single year. . . . While in the beginning the Forest was preponderantly white pine . . . thirty years later there remained only two small remnants of this cover type. Such were the cumulative results of systematic cutting over a period of thirty years under a policy of sustained yield management, and the onslaught of a most destructive hurricane.

THE HARDWOOD ERA AT THE HARVARD FOREST

The hurricane of 1938 provides a date to mark the beginning of the hardwood era at the Harvard Forest. From this time forward, there was practically no old field white pine left to harvest. Thought concerning forest management was thus wrenched into different channels, and new problems had to be faced. Gone was the predominantly biological problem of regeneration, which had dogged the staff during the pine era. The new goal became the production of hardwood sawlogs of high quality. Because hardwood regeneration presented no problem, the biological difficulties, as it were, moved to a later point in the rotation. Manipulation of the medium-aged hardwood stands thus became the primary silvicultural operation. Perhaps more serious was the economic aspect of the new management goal, involving as it did the production of quality hardwood sawlogs for a hoped-for market that was virtually non-existent.

A considerable backlog of experience had been built up over the years concerning the early development of the native hardwoods. One of the first experimental cuts in the Forest took place in a hardwood stand (p. 41), and the purpose of the operation was the regeneration of the hardwoods. Even in the young volunteer stands where the management aim was the regeneration of white pine, selected hardwood crop trees received early encouragement. For example, as early as 1914, the area that was clear-cut in 1908–09 (p. 39) was weeded in a manner to encourage "better" hardwoods in places. This practice became common as the number of white pines in the young volunteer stands diminished over time. In addition, detailed studies of the characteristics of hardwoods growing in mixed stands were conducted at an early date. Spaeth, Patton, Averill, Averill, and Stevens, and particularly McKinnon, Hyde, and Cline provided a solid body of information useful in the management of the young stands. However, management procedures for the crucial second half of the rotation were largely unknown.

At the present time the oldest of the hardwood stands that have resulted from cutting operations supervised by the Harvard Forest staff are near the mid-point of the rotation. It is therefore too early to assess the results of the experimental thinnings and improvement cuts which have been applied to them. Perhaps the most intensive silvicultural experiments have centered on crown-thinnings. Certain aspects of these experiments have been described by Holsoe (1947, 1948).

Studies of Site Components

The hardwood era differed from the white pine era in that the need for varied lines of research was recognized from the start. Research in the young hardwood stands was not limited to silvicultural experiments, but was expanded to include long-needed separate studies of various site components. The latter category of research had gotten under way before the hurricane in the form of studies of land use, soils, and glacial geology. These were the actual outgrowths of an increasingly ecological approach to silviculture, sparked by the general failure of the white pine regeneration experiments. After World War II, studies of site components were accelerated under the encouragement of the present Director, Professor H. M. Raup.

Most of the studies of environment reviewed in the following pages were concerned with characteristics of the surficial deposits and their relation to the forest cover. Therefore, for the sake of continuity, studies of other components of the habitat will be reviewed first.

Detailed Studies of Past Land Use

One of the most fruitful ideas running through the white pine era at the Harvard Forest concerned the effects of land use upon forest composition. Although known prior to the establishment of the Forest (pp. 13–14), the significance of prior use of the land upon the distribution of pure stands of white pine apparently was not fully recognized at the Harvard Forest at first. But within a short time Fisher (1916) showed that almost all of the pure stands of pine in the vicinity of the Harvard Forest had originated on cleared land, and he worked out in a general way the past patterns of settlement, land clearing, and land abandonment (pp. 47–49). He also warned that all abandoned farmland did not develop pure stands of white pine.

During the late 1930's, Raup and Carlson (1941) made a detailed reconstruction of the history of land use in the Harvard Forest. They made a thorough examination of the sequence of land ownership as shown by deeds and other miscellaneous historical records, and by field studies. They mapped the areas within the Harvard Forest that had always remained in forest; and as far as possible, distinguished between plowed land and pasture in the remaining cleared areas. Not only did the past uses of the land thus become known in detail, but the element of time was inserted also. For example, for the first time it became possible to state how long a particular piece of land had remained in pasture before abandonment.

Prior to Raup and Carlson's study, it was generally recognized that a pure stand of white pine within the Harvard Forest reflected an earlier period of land clearing, agricultural use, and subsequent land abandonment. However, the past use of the cleared land — whether as pasture or cultivated field — and the duration of time the area was so used, were not known. Perhaps more important, for the first time it was possible to state whether a particular hardwood or mixed stand within the Forest had originated on land cleared for agricultural use or represented an old woodlot. Theoretically at least, an old woodlot provides a sounder basis for evaluation of the production potential of an area than a stand originating on an old field. This concept perhaps gains added importance in an area such as the Harvard Forest where primeval forest is lacking, particularly when the general goal of management had become the development of second growth forests similar to those of pre-settlement time.

Studies of Microclimate within the Harvard Forest

Another line of research into the nature of environment was concerned with local variation in climate within the Harvard Forest. A general interest in the collection of weather data had existed for many years. This has been summarized by Spurr (1950, p. 164):

> . . . Precipitation records have been taken since 1913 in cooperation with the Metropolitan District Water Supply Commission and more recently in cooperation with the U. S. Weather Bureau. . . . From time to time, special weather studies have been carried on, such as the work on the relation of weather to forest fire hazard (Stickel, 1928), and on solar radiation (Gast, 1930). Hygro-thermograph records, checked weekly by Weather Bureau type maximum and minimum thermometers, have been obtained intermittently at the Headquarters building since 1936 and regularly since 1939.

Studies by Spurr (1950, 1956) and Rasche (1958) provided a body of information concerning microclimatic variation, chiefly local temperature differences, throughout the Harvard Forest.

Spurr (1950, pp. 163–181) made a reconnaissance study of climatic variation within the Harvard Forest for a two-year period beginning in the fall of 1943. This was primarily a study of the local variation in air temperatures, although some data were collected concerning evaporation and soil temperatures. The magnitude of temperature variations that

Spurr found can be illustrated by the range in the length of frost-free periods at different localities within the Forest. During the growing season of 1944 the longest frost-free period was 161 days at the crests of the highest hills in the Harvard Forest (altitudes up to 1383 feet); and the shortest frost-free period was 77 days in the valley of the East Branch of Swift River (altitude 740 feet).

From his studies of local temperature regimes, Spurr concluded (p. 179) that "in concave areas, both high and low in relative elevation, where air drainage is poor, the maximum temperatures are higher, the minimum temperatures are lower, and the frost-free season is a great deal shorter than in convex areas characterized by good cold air drainage". Spurr believed that "vegetation modifies the local climate even to a greater extent than does topography" (p. 180), and that the local climates, in turn, influenced forest composition "to a major extent". Noting the absence of proof of these interrelationships, he offered the following illustration of the complexity of the environmental relationships (p. 180):

> The same factors that make a soil very well drained are apt to insure good drainage of cold air and to indicate a site with lower maximum and higher minimum temperatures than would be indicated by a regional climatic average. Thus, a very well drained site is apt to have a moderated climate suitable to plants of a generally southern distribution. Likewise, a very poorly drained soil is apt to result from a topography that inhibits the drainage of cold air as well as of water. Thus, the very poorly drained sites are apt to be characterized by temperature extremes and a short growing season, and thus might prove suitable for plants of a generally northern distribution.

Nevertheless, "there is relatively little evidence that species occurring near the northern edge of their range are found on the high slopes with good cold air drainage" (p. 181).

During the period August, 1947, to July, 1948, Rasche made detailed studies of local temperature differences at 53 localities in the Harvard Forest. He found that local temperature variations within the Harvard Forest encompassed much of the range of temperature variation found in New England. However, all temperature variations came within the limits of Koeppen's (1923) Dfb type of climate. Rasche believed that much of the variation within the Harvard Forest at a point in time was the result of temperature inversions, or the gravity flow of cool air from ridge crests to valley floors. Rasche summarized (p. 102) his findings as follows:

> At Harvard Forest . . . differences in topographic form, direction of

exposure, and vegetative cover are all more important than elevation in determining temperature differences; nevertheless, the effect of elevation by day and of topographic form, together with elevation, by night is such that the ridges have a more moderate climate than the valleys. Because the air can move almost without hindrance above the upland surface, the ridgetops come under a more nearly uniform atmospheric influence than the valleys. The effect of the freely moving atmosphere upon the ridgetops is similar to that exerted by the ocean upon the climate of the land at its margins. In a sense, the ridgetops have a mild type of climate. . . . The valleys, by contrast, have greater extremes and have more severe climates.

Studies of the Surficial Deposits

Cline and Lockard provided both a plan of management for mixed pine and hardwood stands and a general system of site evaluation to permit its application to a specific area. Similarly, McKinnon, Hyde, and Cline provided a management plan for a variety of volunteer hardwood types and a somewhat different system of site evaluation. Together these systems promised to provide a more rational method of managing forested land. Both systems required a careful analysis of site, chiefly the soil materials. Both systems further pointed up the urgent need for rigid morphological criteria for characterizing soil materials on the basis of the deposits themselves, and not on the basis of the trees which the deposits supported.

Fisher (1928) and Griffith, Hartwell, and Shaw had provided a mass of information concerning the superficial layers of the soils; but Griffith, Hartwell and Shaw concluded that in forests up to 80 years of age the trees themselves produced the soil characteristics that foresters used to classify forest sites. As has been shown, McKinnon, Hyde, and Cline turned back to the same terminology for describing site differences that had been used from the beginning at the Harvard Forest, with additional characterizations of the organic layers based upon the work of Griffith, Hartwell, and Shaw.

Until 1938 the only comprehensive information concerning the surficial deposits themselves was contained in the comparatively small-scale reconnaissance soils map of Worcester County (Latimer, Martin, and Lanphear). In that year a study of the glacial deposits in the vicinity of the Harvard Forest was made (Upson). This was followed by the preparation of large-scale soils maps of the Forest (Simmons, 1939, 1940, 1941), which greatly stimulated research in relations between soils and vegetation (Lutz and Cline, 1947; Spurr, 1950, 1956). Further investigation of the surficial deposits resulted in a blending of the concepts of glacial geology and pedology that promised to be more useful in site evaluation than either separately (Stout, 1952). This line of research was continued (Hatheway, 1954; Patric, 1956) and, in combination with studies of the effects of tree-throw upon soil characteristics (Stephens, 1955a, 1955b), has led into a thorough re-examination of the problem of soil genesis, classification, and mapping in a small area within the Harvard Forest (Coates and Lyford, in prep.).

STUDIES IN GLACIAL GEOLOGY

The first detailed study of the glacial materials in the vicinity of the Harvard Forest was that of Upson, who mapped and described the surficial deposits. Upson recognized three types of glacial deposits in the Petersham-Athol area (p. 7):

> . . . stratified drift, or sand and gravel, outwash, or kame deposits; unstratified drift, or till; and an additional thin disturbed and structureless layer called warp, lying on both the gravel and the till.

In the Harvard Forest, Upson mapped stratified drift in valleys at altitudes of less than 900 feet.* He described the stratified drift as follows (p. 8):

> The color of the sand and gravel ranges from almost white to very dark brown. The latter is accompanied by heavy iron staining, and a little encrustation of the larger boulders in which some smaller stones and pebbles may be bound. The amount of staining of the stratified beds appears to be closely related to the size of the fragments, and hence probably to the permeability of the material. Invariably the coarse gravel deposits are the most heavily stained. The sands are yellow colored, and the finest sands and silt beds are nearly white. Considerable variation is visible even in the same pit. Coarse gravel layers, heavily stained, may be seen separated by much finer layers relatively unstained.

Upson found lacustrine deposits essentially absent, and attributed most deposits of stratified drift to glacial stream action. Topographic features of some of the deposits suggested lingering ice tongues in the valleys and ice stagnation. Stratified deposits in the uplands were found to be fine-grained, dominantly sandy.

Most of the area included in the Harvard Forest was mapped by Upson as "thin till with some bedrock outcrops" (Fig. 3). The distribution of the till was described as follows (p. 9–10):

> The till occurs as a thin mantle over most of the area but mainly on the

* See Stout, 1952, Fig. 1, for topographic map of the Harvard Forest; also Athol and Petersham quadrangles, U. S. Geological Survey, topographic maps, 7½ minute series.

> flanks of the hills, and in a few protected depressions. There are no large masses in the valleys, though the presence of "stone and loam", or "clay and stone" is reported below the stratified drift by workers in the gravel pits. It is probably safe to assume that thin till underlies the gravel deposits in most places. . . .
>
> Bed-rock outcrops occur in abundance on the hilltops and just below the brows of the hills. In those places the mantle of till is either very thin, or entirely absent. There are very few till masses of any appreciable thickness.

Upson noted that the till is predominantly sandy in texture, with some silt but very little clay; and that most of the till is loose, with a few bodies of compact, somewhat finer-grained, uncemented till. According to Upson, the principal differences in the till are differences of color, which "ranges from bright, almost white or gray, through various shades of darker gray, or drab, to dark brown, or almost reddish brown" (p. 11). He found a relation between the color of the till below the stained layer and the nature of the underlying bedrock (p. 12):

> In a general way the distribution of the drab till corresponds with that of the Hardwick granite; the dark or brown till is associated with the Brimfield schist; and the bright gray, or blue gray till is almost entirely restricted to the area of outcrop of the Monson granodiorite.

A general study of the pebbles contained in the till showed a similar relationship between pebble types and the color of the till.

Upson thus related the color and pebble content of the till to the underlying bedrock. This had been done in a general way by Latimer, Martin, and Lanphear, who noted that the "three well-defined north-and-south soil belts" (p. 1547) in their map of Worcester County soils "are due to three north-and-south belts of somewhat different kinds of rocks" (p. 1548). Fisher (1928) and Griffith, Hartwell, and Shaw, in their studies of soils at the Harvard Forest, hardly considered the till, and ignored the bedrock.

It was in his geologic approach to the upper layers of the soil materials that Upson differed most from Latimer, Martin, and Lanphear, Fisher (1928), and Griffith, Hartwell, and Shaw. Immediately beneath the organic litter, Upson recognized a disturbed, presumably frost-heaved layer, which we called "warp,"* which was universally present on all glacial deposits, both stratified and unstratified (p. 18):

> In the Petersham-Athol area the warp consists of dominantly fine-grained material studded with a relatively few large pebbles, boulders and other

* See Denny, 1938.

fragments. Because of such a tremendous amount of fine-grained material in the warp, even where it overlies coarse gravel deposits, the writer believed that there is in most places a considerable admixture of wind-deposited fine sand or silt. In general this material, the warp, is loose-textured, exhibits neither stratification where it overlies gravel, nor till structure where it overlies till, and is everywhere heavily stained with limonite.

Many of the large fragments are rounded and are apparently derived from the underlying material. On till outcrops, mostly situated near or on hillsides, other fragments are sharply angular and obviously derived from bed-rock outcrops farther up the slopes.

Upson offered four lines of evidence that indicated the warp was formed sometime in the past (p. 19):

1. Talus slopes, or Blockmere, contain only weathered rock fragments. Frost-riven blocks which have moved only a few inches possess a soft outside rind, and rounded, smoothed corners.

2. In a few places, huge angular blocks, 10 feet across or more, occupy places to which they could hardly have been moved under present conditions on the observed low gradients.

3. Large trees, in undisturbed attitudes, grow among many of the accumulations of blocks. . . .

4. The warp itself is everywhere heavily iron-stained to a depth of from 1½ to 2½ feet, suggesting its formation previous to weathering. In a few localities . . . there is some indication that the disturbed zone, or warp, is thicker than the surface staining, and extends below the lower limit of that staining. This constitutes a positive indication that the warp was formed before surface weathering began, although the evidence is not clear-cut.

Upson then offered the possibility of ancient origin of the warp (p. 19):

If the formation of the warp occurred in some past interval of time, it may well have been during the so-called peri-glacial interval, accompanying the retreat of the last ice. The writer believes, however, that the evidence at hand in favor of antiquity of the warp in this area is not conclusive.

Upson believed that the long, smooth, boulder-strewn slopes, the thin till on hilltops and absence of knob and kettle topography characteristic of ground moraine, and the warp (if ancient origin was assumed), possibly indicated intense frost action along the edge of the retreating ice front.

The geologic concept of warp as a structureless, disturbed layer derived from the underlying drift, containing eolian additives, and weathered to the degree that it is heavily iron-stained, is in marked contrast to a pedological concept of climatic and vegetational control over the development of a solum, or true soil. Upson ignored the influence of organic matter in the formation of a stained superficial layer of soil material. By contrast, Fisher (1928) and Griffith, Hartwell, and Shaw ignored iron-staining, and described the superficial layers as horizons enriched with organic matter from the surface, which produced their characteristic colors. Latimer, Martin, and Lanphear (p. 1547) attributed the brown color of the superficial layers "partly to some oxidation of the iron in the soil minerals and partly to the organic matter". The solum of pedologists is roughly equivalent to "the customary stained layer, 2 to 2½ feet thick, which is part of the upper layer of warp" of Upson (p. 12). The presence of warp below the limit of staining suggests that the so-called parent material of the soils consists of warp, at least in part. In other words, Upson's warp concept implies that the parent material is actually warp, which has been derived from the underlying drift with an added eolian component, and not the drift itself.

Now, for the first time, the materials were available for a general understanding of the whole body of the surficial deposits and their relations to the underlying bedrock. Fisher (1928) and Griffith, Hartwell, and Shaw had provided a large body of information pertaining to the physical and chemical properties of the superficial layers of the soil materials. These studies emphasized the nutritional aspects of the soil and the biological influences exerted upon the superficial layers. Latimer, Martin, and Lanphear had described the superficial layers as geologic deposits that had been slightly modified by pedological processes. They subdivided the glacial deposits on the basis of petrographic composition, and recognized stratified drift and till, as had Upson. Upson interpreted the superficial layers in terms of past geologic processes, and recognized weathering of the iron minerals as a process of change that had continued into the present.

STUDIES IN SOILS

Detailed Survey of Soils within the Harvard Forest

In June, 1939, a meeting of soil scientists and foresters was held at the Harvard Forest to discuss the problem of soils mapping in forested land. C. E. Kellogg, Chief of the Soil Survey Division of the U. S. Department of Agriculture, observed that the Soil Survey mapped and classified forest soils using soil characteristics of known importance to agriculture. He invited the foresters to make suggestions for the improvement of soils mapping under forest. After four days of discussion, the conference reached the following conclusions:

(1) No changes are recommended in the Soil Survey mapping methods at this time.

(2) Soil Survey maps "gave promise of being useful in forest management".

(3) Detailed soil maps are desired on the experimental forests of the Northeastern Forest Experiment Station, the Fox, Yale, and Harvard Forests and perhaps others.

- (a) Soil mapping should be done independently of forest type mapping.
- (b) Organic horizon types should be identified.
- (c) Indicator species distribution should be mapped.
- (d) Quarter-acre sample plots should be placed, if possible, on single soil types. (Sample plots already established should be graded according to homogeneity for soil type.)
- (e) Analyses of possible correlation of soil types and site qualities should be attempted.
- (f) The possibilities of foliar diagnosis for nutritional levels and availability of nutrients in the soil should be explored.

During the summers of 1939, 1940, and 1941, the soils within the Harvard Forest were mapped at a scale of 200 feet to the inch by C. S. Simmons, of the Soil Survey Division of the U. S. Department of Agriculture. Simmons used established agricultural soils map units. Nine soil series, presumably derived from till, and seven soil series, presumably derived from stratified drift, were mapped. The soils series designations further recognized 1) composition of the so-called parent material, i.e., of the till or stratified drift; 2) drainage; 3) thickness of the deposit; and 4) consistence of the deposit (Table 5). These sixteen series were further subdivided into 34 soil types on the basis of the texture of the plow layer. In addition, ten miscellaneous categories were mapped, such as peat, muck, recent alluvium, and made land.

The Peru series (Table 5) is a member of the Podzol great soil group (U. S. Dept. Agriculture, 1938, p. 1021). Whitman and Scarboro series are Half Bog soils, generally mapped within the Podzol and Brown Podzolic regions. The remainder of the series listed in the table belong to the Brown Podzolic great soil group.

Simmons (1941) provided a general description of the Brown Podzolic soils within the Harvard Forest:

> These are characterized by a thin accumulation of organic matter on the surface, 3 to 5 inches of dark-brown surface soil and a yellowish-brown subsoil. In some places there is an incipient Podzol profile consisting of a thin gray layer (bleicherde) about one-half inch thick and a dark-brown

TABLE 5

CATENA KEY TO SOIL SERIES MAPPED BY SIMMONS AT THE HARVARD FOREST

Substratum	*Well to Excessively Drained*	*Imperfectly Drained*	*Poorly to Very Poorly Drained*
Wisconsin till derived mainly from granite or granitic gneiss			
1. shallow to bedrock	Gloucester, shallow phase		
2. deep, friable to firm	Gloucester	Acton	Whitman
3. deep compact, platy	Essex		
Wisconsin till derived mainly from gray mica schist			
1. shallow to bedrock	Charlton, shallow phase		
2. deep, loose	Grafton		
3. deep, friable to firm	Charlton	Sutton Peru	Whitman
Wisconsin till derived mainly from brown rusty pyritiferous schist			
1. shallow to bedrock	Brookfield, shallow phase		
2. deep, friable to firm	Brookfield	Sutton	Whitman
Glaciolacustrine or marine olive, neutral to alkaline deposits		Buxton	
Glaciofluvial sands and gravels mainly from granite or gray mica schist	Hinckley (kames) Merrimac	Sudbury	Scarboro
Glaciofluvial sands and gravels from granite, gray mica schist and some rusty pyritiferous schist	Jaffrey (kames) Barnstead	Sudbury	Scarboro

upper subsoil (orterde) about 2 inches thick. These horizons are normally found only where the land has been continuously in forest and the accumulation of organic matter is 2 or 3 inches thick; but, since practically all of this land now in forest was cultivated or used for pasture within the last century, the organic accumulations and thin surface horizons have been mixed together.

Almost everywhere the soil is structureless but in a few places a weak fine granular structure has developed in the surface horizon. Generally the soil is only moderately firm in place, but in some places the material in one or more horizons is compact or indurated, and in other places it is incoherent.

Simmons' reports (1939, 1940, 1941) often mention the difficulty of classifying the drift. Particularly difficult were the well-drained till soils which, as mapped, constitute more than half of the Forest area. The scrambled state of the drift as viewed by the soil scientist can be illustrated by the following excerpts from Simmons' report on soils in the Pom Swamp Tract (1939, pp. 11–12):

> All horizons [of Gloucester stony fine sandy loam] are somewhat finer textured than most areas of Gloucester fine sandy loam mapped elsewhere in New England. In some places small amounts of bluish or reddish-brown schist have been included in the composition of the till. Small isolated spots can be found within the area mapped Gloucester stony fine sandy loam where the soil is Charlton stony loam and others where it is Brookfield stony loam. The boundaries between Gloucester and these other soils are, in many places, indistinct and are more or less arbitrarily drawn where there is a gradual transition from one soil to the other. . . .
>
> The boundary between this soil [Charlton stony fine sandy loam] and Merrimac loamy sand is difficult to determine and in a few places small areas of Merrimac fine sandy loam may be included in mapped areas of both Charlton soils. In some small spots the substratum is light gray, rather gritty, and resembles the substratum of Gloucester soils.

Not only were the three categories of till difficult to distinguish and map, but till (Charlton) was difficult to separate from stratified drift (Merrimac).

Simmons' statements point out the difficulty of classifying and mapping soils series that are defined in terms of the lithology of coarse fragments in the substratum. In glaciated regions that are underlain by a complex bedrock system, classification on this basis is particularly difficult. Emerson's map of the bedrock (1917) shows that all three tracts of the Harvard Forest are underlain by Hardwick granite, except for the extreme western end of the Prospect Hill Tract which is underlain by Brimfield schist. However, the Tom Swamp Tract is almost surrounded by Brimfield schist, which also lies immediately to the west and north of the Slab City and Prospect Hill Tracts. The movement of the Wisconsin ice sheet across the region from the north or northwest has resulted in a mixing of fragments from the different rock formations. Furthermore, the rock formations as described and mapped by Emerson are highly variable. For example, note Emerson's description of the Brimfield schist (p. 69):

> The Brimfield schist occupies a large part of the western half of Worcester County and extends west, north, and south far beyond the limits of the county. It is very generally so soaked with granitic material in small lenses, veins, and filaments that it has become a composite rock or a gneiss which still retains largely the aspect of the schist from which it was derived. Where least contaminated by granitic material it is a coarse deep-brown biotite-muscovite schist in which the red-brown shade of the biotite is very common.

Not only does the drift consist of all combinations of the local rock formations but the different rock formations are also highly variable.

The variability in composition of the drift apparently forced Simmons to abandon petrographic criteria to a large extent. According to his reports, the Charlton-Gloucester-Brookfield complex was separated largely on the basis of color and texture.

The difficulties inherent in the classification and mapping of highly variable drift deposits were compounded by the extremely large map scale used by Simmons. The agricultural map units and mapping procedures available to him had been developed for use at much smaller map scales. In other words, the map units were hardly comparable to the scale of mapping and, as defined, might not be mappable at all. All these difficulties resulted in a soils map which, in some areas, probably possessed more variation within a single map unit than between different map units.

Simmons' descriptions of the substratum of Charlton soils suggest that the till had been derived from fine-grained strata within the Hardwick granite, and from the Dana diorite and Monson granodiorite which crop out immediately to the north and west of the Forest (Emerson, 1917). Upson (p. 12) found gray till overlying Hardwick granite, one body of which contained "mostly fragments of the light, fine-grained phase of the Hardwick granite". Simmons' Gloucester catena probably roughly approximates Upson's "drab colored till", underlain by Hardwick granite; the Brookfield catena of Simmons probably roughly approximates Upson's "brown till" underlain by Brimfield schist. Upson claimed only a general correlation between the till and the rock formations, and observed that an almost continuous color transition existed in the deposits. Upson's smaller map scale might bring out a general relationship between till color and bedrock that would be obscured by such a large map scale as was used by Simmons.

The detailed soils map of the Harvard Forest provided the most comprehensive information concerning this major component of site yet available. However, the validity of agricultural soil map units for forested lands was yet to be tested. The divergent views of the surficial materials as seen by a glacial geologist (Upson) and a pedologist (Simmons) suggested a need for clarification and reconciliation of viewpoints.

Evaluation of the Detailed Soils Map

The first test of the usefulness of the soils map was provided by Lutz and Cline, who summarized the results of efforts to control by silvicultural means the composition of stands following the cutting of old field stands. Their report presented the material in the form of case histories for twelve old field white pine stands and two old field hardwood stands "representative of the reproduction methods tried out by the Harvard Forest staff, of the results obtained under differing site conditions, and of the varying cultural treatments applied to the new stands" (p. 167). In brief, Lutz and Cline found that pure hardwoods or mixed pine and hardwoods had followed the cutting of old field white pine that had grown on upland till soils, and pure hardwoods had followed the cutting of old field hardwoods. The 30-year report is unusual in that it recounts in detail the total failure of a large segment of the silvicultural manipulations at the Harvard Forest. At the same time, it documents the old field white pine-hardwoods succession in central New England and emphasizes the importance of the ecological foundations of silviculture.

Lutz and Cline (p. 168) found a close relationship between stand composition and soil characteristics in the stands that followed the cutting of old field white pine:

> . . . in the case of old field stands on heavy soils, the results are practically the same regardless of the reproduction method applied. The strong tendency of hardwoods to follow old field pine was not successfully counteracted by any of the reproduction methods employed or by subsequent weedings to favor the pine. At best, the new stands contain only a minor portion of white pine, or other softwoods; and this portion is subject to still

further shrinkage with time. On the medium soils, the proportion of white pine, or other softwoods, in the new stands is decidedly greater. Most of these stands may fairly be called mixed white pine and hardwood. On the light soils the proportion of white pine is still greater, though there are too few cases on light soils in the Harvard Forest to permit determining the measure of the increase.

The conclusion is inescapable that soil is the predominant factor in determining the outcome of reproduction methods and that attempts to encourage species not in the natural line of succession for a given site prove unsuccessful and costly beyond all hope of return commensurate with the outlay.

Although the relationships between soils and stand composition were stated in terms of the three-way classification of soils proposed by Cline and Lockard, Lutz and Cline attempted to fit the Soil Survey map units into the rude Harvard Forest system. Thus, "heavy soils" was equated with the following soil types (ftn. p. 168):

Charlton stony loam, Charlton stony fine sandy loam, Charlton stony silt loam and certain types within the Gloucester series which have highly favorable moisture relationships. The term "heavy soils" is here equivalent to "best sites," where total height for the leading hardwood species at 50 years ranges from 65 to 70 feet.

The term "medium soils" was similarly equated with (ftn., p. 171)

Gloucester stony fine sandy loam, Gloucester fine sandy loam, and Brookfield stony loam. The term "medium soils" is here equivalent to "medium sites," where total height for the hardwood species at 50 years is around 60 feet.

In the one case involving "light soils", the stand was growing on soil materials mapped as Hinckley loamy sand.

Lutz and Cline's general evaluation of the soils as mapped by the Soil Survey is indicated by the following quotation (pp. 14–15):

Locally, the Brookfield soils are most common. . . . Other common upland soils are those in the Gloucester and Charlton series. . . . The subsoils and substrata are heavier in the Charlton soils than in either the Brookfield or Gloucester, thus making for better moisture retention and higher productiveness.

Scattered throughout the uplands are soils which are imperfectly drained, exhibiting characteristic mottlings and having a high water table. Such are the Whitman and Sutton soils. . . . Both are considered highly productive.

Some soils, occurring less commonly, developed under deficient moisture conditions; these have been derived from water-laid materials, mainly sands

> and gravels, and are located along the present main waterways. Some were laid down as smooth plains, others as low rounded knolls. The former group includes the Merrimac and the latter the Hinckley soils. These two lighter soils constitute the natural habitat of the pines — white, red, and pitch.
>
> With respect to native fertility and forest productivity, the three most common upland soils are fairly comparable, though the Charlton, as had been stated, is perhaps slightly more moist and therefore somewhat more productive than the Brookfield and Gloucester. The Sutton and some of the better-drained Whitman soils are at least equally productive.

Lutz and Cline, using Simmons' soils maps, did not lump the Gloucester, Charlton, and Brookfield series, as did Griffith, Hartwell, and Shaw, who used Latimer, Martin, and Lanphear's reconnaissance soils map. Instead, Charlton and an unspecified part of the Gloucester soils were considered to be moister than the Brookfield and part of the Gloucester soils, and thus more productive. Some of the soils mapped as Whitman were considered the equivalent of Sutton soils, implying a further subdivision of the soils map units. These rearrangements were made simply by juggling the mapped soil types and lumping soil series. The result was a three-membered soils classification that seemed to be more useful for forestry purposes than Simmons' three-membered catena based upon Soil Survey drainage criteria.

A large part of the cultural treatments described by Lutz and Cline were aimed toward the encouragement of white ash and the control of the tendency of red oak to dominate the stand. The treatments were successful in varying degrees, and apparently the results were related to differences in the soil materials. Hardwood stands growing in areas of generally heavy soils showed almost invariably an increase in dominance of the red oak in the better drained parts of the area. On the moister parts of the site, white ash tended to predominate. Stands growing in areas of generally medium soils showed hardwoods, predominantly oaks, on the moister parts of the site, and white pines on the drier parts. These facts led Lutz and Cline to recommend efforts toward a groupwise distribution of species in medium and heavy soil complexes to take full advantage of minor variations in topography and soil moisture.

Lutz and Cline related the initial distribution of red oak and white ash in the old field stands to the different methods of seed dispersal. They believed that white ash seeds, windborne, come to rest in the vicinity of seed trees, whereas acorns, mostly rodent-borne, might be scattered over a large area. However, as had been shown by McKinnon, Hyde, and Cline, many of the cases disclosed that the initial distribution, or rather the initial proportion of seedlings of the two species, became modified as the oak trees waxed and the ash trees waned. The evolution of red oak dominance took place in spite of continuous efforts to favor white ash by weeding and thinning. In other words, the accidental distribution of the seedlings was rather rapidly modified, and this modification was found to be related to differences in the soil materials.

Another method of testing the soils map, the superposition of the soils map and a forest type map to search for coincidence of boundaries, was employed by Spurr (1950, 1956). The Harvard Forest stand map series goes back to 1908, but the earlier map units were quite general. Representative are such categories as "Hemlock", "White Pine", "Good Hardwoods", and "Poor Hardwoods"; and the criteria apparently varied over time. In 1946 and 1947, S. H. Spurr and associates prepared a new series of stand maps for the Forest, using aerial photographs supplemented by ground reconnaissance. These stand maps were intended to eliminate the value connotations of the earlier stand maps (Spurr, 1950, p. 16): "For the first time, an effort was made to list the actual species present according to their relative importance in individual stands, and to assign height and density values to each stand".

By means of the aerial photos, "the stands were classified according to (1) broad composition classes as softwood, mixedwood, or hardwood; (2) ten-foot height classes; and (3) four density classes" (Spurr, 1950, p. 76). The boundaries of all "homogeneous forest areas" larger than 0.25 acre, were then transferred to a base map having a scale of 400 feet to the inch. The ground reconnaissance consisted of the following (p. 76):

> The maps were then taken into the field, and each stand checked on the ground. To replace the broad type classification, the species making up the stand were listed in order of abundance. Trees of primary or major abundance were listed in the numerator of a fraction, and trees of secondary or minor abundance were listed in the denominator. No hard and fast line was recognized between the two groups, but trees making up more than 10 per cent of the basal area were generally considered of primary importance and those making up less than 10 per cent were of secondary importance. . . . Normally not more than four species were listed in either the numerator or the denominator of the type fraction.

According to Spurr (pp. 76–77), "the result of the typing and coding system was a flexible description of the stand composition and structure as it actually occurred on the ground without recourse to any arbitrary or preconceived classification system".

The claimed homogeneity of stands as determined from aerial photos, at least as to their species composition, is open to doubt. Within a stand classified as "hardwood", for example, a uniform distribution of its component species is an unlikely possibility. Lutz and Cline showed that groupwise distributions of species were common within hardwood stands; and they further showed that the distribution of species within a stand was related to differences in the soil as mapped. Thus the possibility exists that a homogeneous hardwood stand as shown on the stand map consists of a hardwood stand of variable species composition, but of uniform density and height.

Spurr attempted to determine the principles underlying the distribution of the tree species and forest types as shown by his stand map. In analyzing the present distribution of the tree species, he (1950, p. 78) restricted his study to "stands covering at least one acre, to areas of natural stocking, to stands 25 feet or more in height, and with a C stocking or better (more than 30 percent of the area covered by tree crowns)". A further restriction was inherent in the fact that the composition data for each stand generally were limited to four "major" species and four "minor" species, in stands that might contain as many as twenty species of trees.

The procedure was further described by Spurr (pp. 78–79):

> . . . each stand was designated on the basis of field reconnaissance according to successional stage and moisture relationships of the site. . . .
>
> Three successional stages were recognized: (1) pioneer, (2) transitional, and (3) late successional. The distinction was relative rather than absolute. Pioneer stands included all those known to have originated on old fields and following clear-cutting and fire in the past twenty to thirty years. . . . Transitional types included all middle-aged stands not segregated as pioneer or late successional. Late successional types included all old-growth remnants, and all areas in which no cutting or other disturbances have taken place over the past half-century or more. Although the segregation of successional stages was somewhat subjective, it proved surprisingly easy and apparently fairly precise.
>
> Five soil moisture conditions were recognized. . . . The base of the classification was the Harvard Forest soils map, modified where necessary by field reconnaissance. Generally, but not always, Merrimac, Hinckley and Jaffrey soils were considered very well drained; Gloucester, Charlton, and Brookfield soils were considered well drained; Acton and Sutton soils were considered imperfectly drained; Whitman soils were considered poorly drained; and peat and muck deposits were considered very poorly drained.

Spurr stated that "when all the stands were sorted according to the above criteria, it was found that each class thus set up was characterized by a distinctive stand composition" (p. 79). He summarized these relationships as follows (pp. 102–105):

> Two species are practically omnipresent. Red oak and red maple are equally prominent on all successional stages and one or the other is prominent on all sites . . . both exhibit marked relationship to soil moisture, red oak being most frequent on the drier, and red maple on the wetter, sites.
>
> White pine . . . is . . . the characteristic old field tree. Furthermore . . . it is the characteristic tree of very well drained sites in all successional stages.
>
> . . . White pine . . . appears to be a minor but important and characteristic component of late successional stages on all sites from the wettest to the driest.
>
> Hemlock occurs in more or less equal numbers in late successional stands on all sites. It occurs but infrequently in pioneer and transitional associations, but is the characteristic species of late successional stands.
>
> Of the other species, the various birches are the most important. Paper birch is best adapted to the drier sites, black birch to the average well drained sites, and yellow birch to the wetter sites. White ash is locally important on the imperfectly drained soils, but shows little persistence into late successional stages. White oak is important in all successional stages on the drier soils, while hickories are somewhat less xerophytic, being found on the well drained as well as on the very well drained sites. Beech and sugar maple are occasionally found on the intermediate sites; while red and black spruce, tamarack, elm, and black gum are found on the wettest sites.

The neat interrelationships between stand composition, successional stage, and soil drainage found by Spurr are rather surprising when viewed in the light of his critique of the Harvard Forest soils map (1950, pp. 129–145). The soils included in the five drainage classes used by Spurr are the same mapped soil types that had been segregated into three drainage classes by Simmons. In other words, Spurr did not re-map the soils but depended upon Simmons map and "field reconnaissance" of an unspecified nature for his soils separations. Nevertheless, he doubted the validity of the soils classification and the accuracy of the boundaries of the soils map (pp. 129–130):

> In working with the soil maps of the Forest over a period of years, in accompanying the soil surveyor in his work, and in trying to correlate forest composition and growth with established soil types, it became evident to the author that hard and fast distinctions between the various soil types are difficult if not impossible to make, and that soil classifications must fre-

quently be taken with a grain of salt. Parts of three summers were spent in preparing the soils map of the Harvard Forest. Nevertheless, despite this large amount of time spent only on about two thousand acres, the distinctions between many soil types are by no means clearcut and the resultant soil maps cannot be considered by any means as definitive. Upland soils derived from glacial till on the Harvard Forest intergrade freely from Gloucester to Charlton to Brookfield. None of the soils mapped as belonging to these series in the Forest are typical or classic examples. Distinction between Acton and Sutton soils is similarly hazy.

Spurr's approach to the soil materials in the Harvard Forest was geologic; and he clearly saw the relationships between the complexities of the bedrock and the soil materials which "are highly complex and vary widely within short distances" (p. 122). He rejected as a means of developing soil taxonomic units the biological approach to soil formation that had been used at the Harvard Forest by Fisher (1928), Griffith, Hartwell, and Shaw (1930), and Gast (1937) because of the "lack of major differences in the vegetation . . . and the disturbances of the vegetation attendant upon a long period of land-use by man" (p. 126). He concluded (p. 126):

> The local problem of soil classification, therefore, may be reduced to the problem of recognizing areas of uniform parent-material and relief, the latter factor being interpreted to cover variations in moisture relations as well as variations in the surface topography.

Spurr (pp. 130–131) elaborated his recommendations for a forest soil classification in terms of Simmons map units:

> The safest and most useful classification of the soils at the Harvard Forest . . . might well be a generalized one based solely upon mode of deposition of the parent material and upon moisture relations. In practice, such a classification proves quite satisfactory.
>
> Two modes of origin were recognized: (1) soils developed from glacial till, and (2) soils developed from stratified drift, particularly glaciofluvial sands and gravels laid down in kames, eskers, and outwash plains.
>
> Five drainage classes were set up, based largely upon the effect of soil moisture on profile development and permitting the correlation of soils series with drainage classes in so far as possible. Very well drained soils are those zonal soils with a low water table. Under this category come most Hinckley and Merrimac soils and those Gloucester, Charlton and Brookfield soils so located topographically as to be unusually dry (i.e. typically on high, dry ridges). Well drained soils include most Gloucester, Charlton and Brookfield soils and occasional areas of low-lying Merrimac and Hinck-

ley soils with better moisture relations. Imperfect drainage (termed moderately well drained in current Soil Survey nomenclature) refers to soils developed under a water table sufficiently high to cause a mottled soil profile reaching close to the surface. Sutton and Acton soils are thus imperfectly drained. Poorly drained soils belong largely to the Whitman series and include soils with such a high water table that essentially the entire mineral soil profile is colored dark or is heavily mottled up to the surface. Finally, very poorly drained soils are those in which there is a surface layer of organic matter in the form of muck or peat at least ten inches thick.

Thus, both Lutz and Cline (1947) and Spurr (1950, 1956) believed that by simple rearrangement the mapped soil types could be related to stand composition. Their revisions were rooted in the belief that soil moisture, of the many soil properties, was most closely related to species composition. Both revisions segregated soil types belonging to a single soil series, but the revised catenas differed from each other. For example, Lutz and Cline separated Charlton from Brookfield and most Gloucester soils; but Spurr, as had Griffith, Hartwell, and Shaw, lumped Charlton, Gloucester, and Brookfield soils where they occurred in similar topographic positions.

Re-examination of the Soil Materials

Stout, by means of excavations as much as 10 feet deep, restudied the soil materials at selected points within the Harvard Forest. He concentrated his efforts upon upland areas mantled by till where a single forest type occurred on different soils as mapped by Simmons, or where two or more forest types grew upon a single soil type. Thus, unlike Lutz and Cline (1947) and Spurr (1950, 1956), he found little or no relationship between the distribution of those soil types classed by Simmons as well-drained and imperfectly drained, and the distribution of forest types and species.

Stout's deep pits exposed pronounced variations in till consistence within the root zone of the trees. In places, the till was loose to depths of as much as 8 feet. Elsewhere the till contained firm or compacted layers that occurred at depths ranging from 18 to 40 inches. Stout found that the distribution of compact horizons was not reflected in the soils maps. For example, soils mapped as members of the Gloucester series in places lacked compact layers (pp. 18–20); in other places compact layers were present, ranging in depth from 22 to 40 inches (pp. 11–14).

In areas underlain by compact till, Stout found a relationship between topographic form and thickness of the loose overburden. Thus, in places where the surface configuration, or microrelief, was slightly concave to the sky, the compact till generally was found nearer to the ground surface than in areas where the surface configuration was slightly convex.

Stout concluded that the distribution of tree species, both the species assemblages referred to as forest types and local concentrations of species within a stand referable to a single forest type, was related to till consistence. He found that the loose, coarse-grained till deposits generally supported stands consisting of relatively few tree species, "among which red, white, and black oaks predominate, and among which sugar maple and white ash are rare or non-existent" (p. 27). On the other hand, stands growing on compacted, fine-grained till generally contained "a rich mixture of hardwood species in which red oak, white ash, sugar maple, and black and white birch are predominant" (p. 27). Included in the latter category were stands mapped by Spurr as "RO-WA" (red oak-white ash). Stout found that the local distribution of red oak and white ash within stands classed in this forest map unit was closely related to the distance from the ground surface to the top of the compact layer. Thus, if the compact layer lay within about 20 inches of the ground surface, he found that white ash was predominant; if the compact layer lay at greater depths, red oak was predominant. In places where the compact horizon lay generally at about 20 inches from the surface, he found that red oak grew on minor elevations and white ash grew in minor depressions. According to Stout, the composition of stands growing on moderately steep slopes, regardless of the texture and consistency, varies with topographic position.

He further suggested that the observed relationships between till texture and consistence and the distribution of species was the result of differences in moisture regimes. Thus, compact layers near the ground surface would inhibit the downward percolation of water and produce "perched" temporary water tables during the wetter parts of the year. High temporary water tables would produce a moist site favorable for the development of white ash concentrations. The deeper the compact layers, the lower the temporary water tables, the dryer the overburden, the more favorable would be the site conditions for the development of red oak concentrations. Absence of compact layers results in still dryer sites, which would be more favorable for other species of oak.

Stout proposed a series of geologic events and processes to account for the characteristics of the soil materials. Like Upson, he believed that the present configuration of slopes is largely the result of processes caused by intense frost, acting upon the glacial deposits at a time when the ice margin was nearby. As additional evidence of intense frost action, or congeliturbation, he offered the stone-banked, lobate terraces that are common interruptions on otherwise smooth slopes (pp. 23–24). As had Upson, Stout viewed the surface layers of the mineral soil as a geologic deposit separate from the underlying till. However, Stout identified this layer, which he called "loam", on the basis of texture and consistence. The loam was chiefly identifiable by its fine-grained texture as compared with the underlying materials; but where loam occurred over fine-grained, compact till, the loam was looser than the till. Furthermore, Stout believed that the loam was largely of eolian origin, and represented the remnant of a body of loess presumably deposited after the postulated period of most intense frost action. The presence of coarse fragments of rock in the loam led Stout to believe that the eolian deposits were disturbed by frost after deposition (p. 26):

> The only source for these coarse materials is the till or congeliturbates, and it is difficult to conceive of their having got into the loess in such quantities by any process other than congeliturbation. Windthrow of trees has stirred the mixture of coarser materials and loess since the former were added by congeliturbation.

In general, the loam as described by Stout coincides with the solum as described by Simmons. Therefore, if Stout's loessial hypothesis is correct, the parent material of the till soils is loess and not till. In soils terminology this would make any underlying warp or congeliturbate — and the till itself — D horizons, with no C horizon present in the profile. Another possibility is that the compact layers are in whole or in part of pedogenic origin, and constitute a part of the B horizon.

Although Stout used Simmons' soils maps as a starting point for his studies, his approach to the soil materials was geologic. Spurr (1950) had viewed the soil materials as geologic deposits also, but he returned to the mapped soil types for his interpretations of species distribution. Stout, on the contrary, largely abandoned the soils maps as a basis for interpreting species distribution. Like Upson, Stout concentrated upon the till deposits. However, Stout was more interested in texture and consistence than was Upson, and largely ignored lithology. Upson and Stout both emphasized the geologic origin of the distinctive superficial layers, and Stout expanded the line of reasoning that had led Upson to designate a layer of warp.

Though his studies covered only a small area within the Harvard Forest, Stout made the first detailed examination of the soil materials since Simmons had mapped the soils. He subdivided the till deposits on the basis of morphological characteristics that were different from those used by Simmons and Upson, and related the different categories to species composition of the stands. Unlike Lutz and Cline and Spurr, who had rearranged Simmons mapped soil types into new sets of drainage catenas largely on the basis of their classifications of the stands which they supported, Stout classified the soil materials on the basis of the morphology of the materials themselves, and showed that these morphological categories had prediction value in terms of species distribution.

W. J. Gabriel and W. H. Hatheway jointly pursued the study of subsoils that had been started by Stout. They investigated in detail the relations between subsoils, topography, ground water, and vegetation in an 8-acre area within the Harvard Forest that supported a growth of old trees. The area was included in a much larger area mapped by Simmons as Charlton stony loam. By laying out a rectangular grid with points located and mapped at 100-foot intervals, they studied the soils, water tables, and vegetation at about 60 stations within the study area.

The initial investigations were designed to test Stout's hypothesis that compacted horizons in the till soils resulted in high temporary water tables. At each of the stations, shallow pits were dug to the upper limit of the compact horizons, or to a depth of 18 inches where compact horizons were not encountered. Periodic measurements of the distance to standing water, if present, were made by Gabriel and Hatheway from early November, 1951, to mid-June, 1952. Some pits were always dry, some pits were always nearly full of water, but most pits showed a wide fluctuation between these extremes. Hatheway (1954, p. 9) divided the holes into six moisture classes based upon "the pattern of ground-water behavior".

He then enlarged the pits to determine the nature of the subsoils. He found no compact layers in 15 holes, which were excavated to depths ranging from 30 to 46 inches. Compact layers were found in 46 of the pits at depths ranging from 10 to 35 inches. In a few pits, the compact layer was recorded as "doubtful" or "weakly developed" (p. 17). To sum up (p. 17), "in the 61 holes excavated, almost all possible degrees of compactness were found".

A comparison of the two sets of data showed the following (pp. 11–12):

> When the moisture class of a station was plotted as a function of the depth to the tight till, the resulting scatter diagram . . . indicated a fairly close linear relationship. Where the depth to the tight till was less than 18 inches, the station invariably belonged to one of the two wettest moisture classes. On the other hand, where the tight till was 35 or more inches

> below the surface of the ground or where it was lacking, the station always belonged to one of the three driest categories.
>
> These relationships may be stated in another manner. The number of days in which a station was dry (no water standing in the post hole) was plotted as a function of the depth to the tight till. . . . At the 14 stations in which the compact layer was 18 inches or less beneath the surface of the ground, the holes were dry on no more than two of the 29 days on which observations were recorded. At 15 stations no tight till was found, although the holes were excavated to depths of 30 to 46.5 inches. All such stations were dry on at least 24 days; in eight, water was never recorded.

Hatheway summarized the relationships as follows (p. 12):

> The relationship [between depth to tight till and the six moisture classes] obviously is not perfect, indicating that the variation in behavior of the water table is not entirely to be accounted for by parallel variation in the depth to the tight till. Other factors such as degree of slope and differential internal resistance to flow of water caused by roots, stones, and boulders also influence the behavior of the ground-water table. Nevertheless, the presence or absence of a tight till and its depth below the surface of the ground certainly were of primary importance in determining the behavior of the ground-water table on the study area.

The tree species present at each station were recorded. Hatheway's criteria for determining "presence" of a species were rigid (p. 12): "A tree species was recorded as present at a station if its crown was over the hole and its trunk was one inch or more in diameter at breast height". Nevertheless, in terms of moisture classes he found (pp. 12–13):

> White pine was much the most frequent species at the driest stations. . . . Red maple and red oak were common at dry, intermediate, and wet stations; the former was most frequent at very wet holes, the latter at intermediate to dry sites.

In terms of compact layers (p. 13):

> Where the compact subsoil was lacking, white pine was the most frequent species. White ash and red maple were the leading species where the tight till was within 18 inches of the surface of the ground, although white pine was again common in this situation.

At the three stations where white ash was the "primary" species, Hatheway found that the compact layer was within 22 inches of the ground surface. Red oak had a higher frequency than white ash at localities where the depth to the tight till was more than 18 inches, and where the tight till was lacking.

Although Hatheway concluded that soil moisture was an important influence upon the distribution of plants and the development of soil profiles, he stated some strong reservations (p. 25):

> It appears quite evident, however, that site moisture has had an important influence on the distribution of major species of trees on the study area. It may also have influenced profoundly the development of its soils. This is not to suggest that the vegetation of the study area can be comprehended through the study of a single environmental factor, however important. In fact, if the whole habitat were thoroughly understood, the vegetation growing on it would always remain an enigma to the degree that chance events might have determined the establishment of individual plants on sites to which they were not perfectly suited.

He tentatively concluded that the compact layers were the product of soil-forming processes acting upon geologic deposits that possessed certain characteristics and occupied particular topographic positions. He suggested that the compact layers thus should be classed as developed horizons, specifically "fragipans." * Noting that differences in texture between the tight till and the overburden were slight in the study area and that all gradations in compaction could be found, he proposed the hypothesis that the tight till had been derived from the same material as the overlying horizons. He visualized the process as a plugging, largely mechanical, of pores within the soil material by particle-laden water. In this way, the distribution of tight tills was related to soil water and topography (p. 18):

> Where, because of the nature of the topography and the texture of the subsoils, water tended to collect and slowly to percolate through the soil to the permanent water table, so that the solum was nearly saturated for relatively long periods of time, hardpans tended to develop. Where the topography favored rapid runoff or a coarse subsoil allowed rapid percolation, so that the solum was excessively drained, hardpans did not develop.

Hatheway believed that the differences in soil materials within the study area were of sufficient magnitude to warrant the mapping of at

* "Fragipans are found in many gently sloping or nearly level soils in humid warm-temperate climates. These are very compact horizons, rich in silt, sand, or both, and usually relatively low in clay. Fragipans may or may not underlie or overlie a horizon of clay accumulation. They commonly interfere with water and root penetration. When dry, the compact material appears to be indurated, but the apparent induration disappears upon moistening. It has not yet been generally agreed whether fragipans are merely an expression of extreme compaction or are reversibly indurated. Fragipans are found in soils developed from both residual and transported parent materials" (Soil Survey Staff, 1951, p. 243).

least two soil series. This belief was based upon his findings of 1) areas lacking compact layers within an area that was generally underlain by compact layers; and 2) pronounced differences in thickness of the organic horizons. He also questioned the validity of soil drainage classifications based upon the presence or absence and intensity of mottling, and suggested that more study of the problem was needed (p. 25): "A satisfactory soil-drainage classification must be based ultimately on the behavior of the water itself, not on putative indicators of its behavior".

The studies of Gabriel and Hatheway generally verified Stout's belief that the presence or absence of compact horizons and the thickness of the materials overlying compact horizons strongly affected moisture regimes and the local distribution of species. However, on the steeper slopes of their study area, which was immediately downslope from one of Stout's localities (pp. 14–15), the relations were not as precisely definable. Both studies provided valuable information for a revision of soils classification and soils mapping techniques specifically applicable to forested land. In addition, Hatheway reopened the question of the origin of the compact layers and the superficial layers of the soil materials.

Patric (1956) studied and re-mapped the soils in an area of about 20 acres that included a part of Stout's study area. The soil types mapped here by Simmons were members of the Charlton catena. In addition, Patric studied the fluctuations in ground water, and mapped the distribution of tree species.

Preliminary study of the soils by means of a soil auger showed "a well-defined range of moisture conditions closely related to local topography" (p. 7). As criteria for the recognition of moisture differences, Patric used the standard pedological characteristics of color and mottling. He divided the range of characteristics into three categories, which he termed wet, intermediate, and dry. He selected three plots which he believed were representative of each category and studied the morphological characteristics of the soil materials in detail by means of pits ranging from 30 to 40 inches in depth. From these studies he chose for his mapping criterion the color of the soil at 15 inches below the ground surface, and mapped the area at a scale of 60 feet to the inch by means of a soil auger. Additional mapping criteria were topographic form, depth to mottling, and depth to compact layers. Patric correlated his map units with those used by Simmons (p. 10):

> Dry soil is comparable to the well drained classification and closely resembles Simmons' Charlton. Wet soil is comparable to the poorly drained classification and is similar to Simmons' Whitman but probably insufficiently water retentive to fit the present day description of that soil. Intermediate

soils combine the moderately well drained and somewhat poorly drained classifications. They are the transitional areas from wet to dry soils most closely resembling the Sutton of Simmons' map.

Patric measured standing water above the C horizons in the nine pits during the late fall of 1955 and again from mid-April to late July, 1956. His data (Fig. 3A, Tables 1 and 2) show that none of the pits lacked standing water from the time of spring thaw until leaf expansion; although minimum levels of standing water during this period ranged from 4 to 32 inches below the ground surface. These minimum levels occurred on a single day in all pits, and showed an exact relation to Patric's soil categories. In soils classed as dry, the depth to standing water on this day ranged from 24 to 32 inches; in intermediate soils, from 17 to 21 inches; in wet soils, from 4 to 15 inches. Within two weeks after leaf expansion all pits lacked standing water within the solum. This occurred in the pits classed as dry soil between June 12 and June 15; in the intermediate, between June 10 and 15; in the wet soil between June 14 and 18. Following rains that occurred after leaf expansion, all of the pits in wet soil showed standing water, and two of the three pits in intermediate soil. However, none of the pits in dry soil showed standing water after leaf expansion, although as much as 1.75 inches of rain probably fell on the area in a single day. Patric found that the relation between water levels and depth to mottling was not as close as between water levels and his soil classes. Although mottled horizons were found in pits classed as dry at depths ranging from below 28 inches to below 35 inches, the depth to mottling in intermediate soils ranged from 13 to 22 inches, and in wet soils from 13 to 25 inches. This is somewhat peculiar in that mottling was one of the two criteria used by Patric in his initial classification of the soils in areas selected for detailed study. However, his report suggests (pp. 7–8) that microtopographic variation, not soil morphology, provided the fundamental basis for recognizing soil variation.

By means of belt transects, Patric mapped the location of individual trees by species in the "upper crown class" * on 22 percent of the study area. He found that four tree species constituted 84 percent of the upper crown class trees: white ash, 30 percent; red oak, 22 percent; paper birch, 20 percent; and sugar maple, 12 percent. Red maple, black birch, yellow birch, and white pine collectively constituted 14 percent. The remaining 2 percent was made up of occasional basswood, hickory, hop hornbeam,

* ". . . an upper crown class tree may be defined as one having (1) the top of its crown over the midpoints of the live crowns of the adjoining overstory trees and (2) over half its crown with overhead space unoccupied by other crowns, and into which space it can expand" (ftn. p. 15).

elm, gray birch, white oak, and beech trees. Patric later mapped the distribution of all individual trees in the latter category, and concluded that "small numbers and spotty distribution invalidated any conclusions that might have been drawn as to the presence or absence of these species on the various soil types" (p. 16).

The same tree species occurred throughout the area, but Patric found that the numbers and dimensions of individual trees of these species varied. The variation in numbers of individuals permitted him to recognize eight different stands within the study area. He believed that the distinctive characteristics of some of these stands were related to soil characteristics, while others were related to distribution of seed or to silvicultural manipulations.

Throughout the study area, he found a general relation between the number of individual trees of the principal species and his three soil categories. Thus, the number of white ash, sugar maple, and red maple trees per unit area was least on dry soils, greater on intermediate soils, and greatest on wet soils; whereas red oak, paper birch, and black birch trees showed an inverse relation to these moisture categories. According to Patric (p. 16), "yellow birch, usually considered a wet land species, is present in greatest numbers on dry soil while virtually absent on the wet soils". He concluded (p. 23):

> Large numbers of white ash are . . . a statistically reliable indication of wet soil. Large numbers of red oak and paper birch are good indicators of dry soil. High mean percentages of the remaining tree species are not good indicators of soil type.

In stands of the same age, Patric found that the number of trees per acre increased with increasing soil moisture; but the volume of wood per acre, as well as the average volume per stem, showed a reverse trend. His data showed that the height and diameter of trees belonging to a single species were essentially the same regardless of soil differences. However, the dimensions of individual trees varied widely between species. Thus, he concluded that the relation between volume and soil class was the result of a more fundamental relation between species composition and soil class, rather than a relation between growth differentials within a species and soil class (p. 22):

> The larger total volume and the greater growth rate per year of stands on dry soil is explained by the presence of higher percentages of faster growing species [red oak, paper birch, black birch]. The greater numbers of white ash and the maples per acre on wet soil are insufficient to compensate, volumewise, for their slower rate of growth.

Patric thought that the observed relations between species distribution and soil moisture regimes might be explained on the basis of the root morphology of tree seedlings. Briefly stated, his hypothesis held that seedlings having fibrous roots would be less subject to frost-heaving, which presumably is more intense in the wetter soils, than tap-rooted seedlings. Conversely, tap-rooted seedlings presumably would be less subject to drought injury in dry soils than fibrous-rooted seedlings. Thus red oak, whose seedlings develop taproots, might tend to suffer heaving in wetter soils and become reduced in number relative to white ash, whose seedlings (at least in the Northeast) develop fibrous roots. In dryer soils, the tap-rooted red oak seedlings might tend to increase in proportion to white ash during periods of drought.

The area studied by Patric is characterized by a general uniformity of soil materials, topography, vegetation, and land use. For example, the soil materials in the whole area possess compact layers, and the same species of trees occur throughout the area. Therefore, the differences in soils and vegetation and their interrelationships described by Patric demanded extremely detailed study and large map scales. Viewing the soil materials from the point of view of the pedologist, Patric was interested chiefly in the A and B horizons, and his soil mapping techniques were adapted for use with a soil auger. He showed that minor differences in soils that were related to variations in moisture regimes could be detected by study of minor variations in topography in combination with the use of a soil auger, if detailed studies of soil morphology in carefully selected pits were made first. Like Gabriel and Hatheway's studies, Patric's studies verified Stout's contention that the local distribution of species is related to the local distribution of variants in the soil materials, which in turn are related to soil moisture regimes (p. 38):

> Sufficient coincidence exists between units of soil type and of associated forest vegetation to justify the conclusion that soil moisture is or has been a critical factor in species distribution on this portion of Harvard Forest.

The studies of Hatheway and Gabriel, Patric, and most of all, Stout, made important contributions to the knowledge of upland soils derived from till, and to relations between the surficial deposits and the vegetation. Stout applied geologic concepts similar to those used by Upson to certain problems of soil variation that were largely ignored by Lutz and Cline and by Spurr. These variations were not revealed by the soil map units used by Simmons. Working independently of the soils maps, Stout was able to show coincidences between the distribution of species and the distribution of certain characteristics of the surficial deposits, chiefly compacted layers and the thickness of the fine-grained, presumably eolian, overburden. He believed that these features of the surficial deposits had been produced by geological, not pedological, processes at a time when the glacier was at or near the area. The hypothesis advanced by Stout to explain the coincidences between species distribution and distribution of compacted layers utilized, among other things, differences in moisture regimes in the deposits. These differences were not stated in terms of the usual drainage criteria of the pedologist — such things as presence or absence of mottling and the intensity of and depth to mottling — but in terms of the presence or absence of horizons capable of impeding the downward percolation of moisture and the depth from the ground surface to such a horizon.

Hatheway and Gabriel elaborated Stout's methods in an area mostly underlain by a firm or compacted layer, and found a general relation between the levels of temporary water tables and the depth to the firm layer. Like Stout, Hatheway found that the local distribution of species was related to the presence or absence of firm layers, and the thickness of the materials overlying the firm layers. However, Hatheway believed that the firm layers were produced by soil-forming processes acting upon glacial deposits that possessed particular characteristics and occupied definite topographic positions.

Patric used pedological criteria to re-map at an extremely large-scale a small area within the Forest that is underlain by a firm layer. He showed that prior study of soil materials exposed in a few carefully selected pits would permit the use of a soil auger, in conjunction with close attention to minor differences in topographic form, to detect minor variations in the soil materials. Patric's soil map units were described in terms of moisture regimes, and the relations between the units and the local distribution of species confirmed Stout's work. Measurement of temporary water tables verified the separation of soil map units on the basis of implied moisture regimes; but the measurements failed to show that mottling was a reliable indicator of soil moisture levels present during a single growing season. Patric advanced the hypothesis that differences in soil moisture regimes affected the local distribution of species by acting upon the characteristic root systems of the tree seedlings, which differ from genus to genus.

Studies of Microrelief on the Forest Floor

Another line of research in site characteristics, which affects the interpretation of both soil and forest development, has to do with the formation and reduction of microrelief on the forest floor. The hurricane of

1938 emphasized the destruction of forests by strong winds, and the resulting disturbance of soil materials by the windthrow of living trees.

Fisher (1933) believed that many of the characteristics of the virgin forest reflected the work of destructive winds, and Cline and Spurr (1942) applied these ideas to a study of Harvard University's "primeval forest" holding in the Mt. Pisgah region of southern New Hampshire. Studies of the effects of windfall on soil morphology at Yale's experimental forest in southern New Hampshire by Lutz and Griswold (1939) and Lutz (1940) provided new insights into the interpretation of soil profiles; and at the Harvard Forest, the work of Stephens (1955a, 1955b) showed that winds of hurricane force had devastated a small area of the Forest several times in the past 500 years.

Cline and Spurr attempted to interpret changes over time in the pre-Colonial forest remnant in southern New Hampshire. Prior to the hurricane of 1938, they recognized that high winds cause extensive damage in forests by the overturning and uprooting of mature trees, and they believed that "large openings caused in this manner afford favorable conditions for the establishment of such light-demanding species as characteristically occupy clear cuttings or severe burns" (p. 26). The 1938 hurricane destroyed almost all of the mature trees in the area and, according to Cline and Spurr (p. 26), "emphasized the importance of wind as a factor affecting forest succession". They noted the occurrence of similar hurricanes in New England in 1815, 1635, "and undoubtedly in previous centuries" (p. 26). They stated that windfalls as much as 150 years of age could often be identified, and that the presence of pre-Colonial, even-aged stands indicate either severe windstorms or fire. They classified the forest stands into successional and climax stages, and concluded (p. 40):

> The climax composition cannot be attained until after the death of most of the non-climax trees in the stand. Since the maximum age reached by white pine, the longest-lived preclimax species in the Pisgah forest, is not far beyond 300 years, it may be assumed that a lapse of nearly 400 years was necessary for the reestablishment of the climax following a severe disturbance. During this time, the stand was exposed to recurring hurricanes and other disturbances which often destroyed the existing stand, thereby initiating a new succession toward the climax.

Lutz and Griswold observed certain morphological irregularities in the soils of southern New Hampshire, which they attributed to the action of tree roots. Careful study of the phenomena, prior to the hurricane of 1938, led them to a rediscovery of Shaler's work (1891) describing the effects upon the soil of the overthrow of trees by high winds. Lutz and Griswold described and diagrammed the effects of treethrow upon soil profiles in four localities. The treethrows that had created the disturbances had occurred from 10 to about 100 years prior to the time of investigation. They stated (p. 399) that "disturbances of this sort cannot be ignored by students of soil morphology" and concluded (p. 399) that "it is probable that all soils which bear, or in the past have borne, forest stands have been more or less disturbed" by tree roots.

Stephens (1955a, 1955b) made a detailed study of the microrelief produced by treethrow on an area of about an acre within the Harvard Forest. By extremely large-scale mapping (10 feet to the inch, contour interval 6 inches), he was able to outline a total of 62 pairs of mounds and pits. He grouped the microrelief features into six age classes by means of soil characteristics, dates of origin and positions of the associated trees, and the general space relations. These age classes, in turn, were related to the known hurricanes of 1938 (18 mounds and pits), 1815 (8 mounds and pits), and 1635 (15 mounds and pits), and a postulated major hurricane that occurred between 1400 and 1500 (18 mounds and pits). Stephens suggested that other periods of uprooting occurred in 1851 (2 mounds and pits) and between 1730 and 1750 (1 mound and pit).

Stephens found that the mounds and pits occupied at least 14 percent of the forest floor and supported 61 of the 444 living trees greater than 1.5 inches in diameter, or about 14 percent. Of these 61 trees, 50 grew on mounds and 11 grew in pits. Of perhaps greater significance, Stephens' studies showed that the trees and soil materials had undergone in the past disturbances similar to that caused by the hurricane of 1938, perhaps on as many as six occasions and over a period of 450 to 550 years.

Stephens' classification of treethrow mounds into age classes, in connection with his profile studies in the disturbed soils, promises to be of value to students of soil genesis working in the area. By these means, rates of formation of Brown Podzolic profiles can perhaps be estimated more reliably. In terms of relations between the nature of soil materials and the local distribution of species, his study of microrelief is also of importance. According to Stout, about 95 percent of the roots of trees occur above the firm layers in the soil. Therefore, the disturbances to the soil materials produced by windthrow probably are confined largely to the loose overburden. However, disturbances in this part of the profile may result in local alterations of the depth to the firm layers, and therefore affect the local distribution of some species.

DISCUSSION

The course of events during the first 50 years at the Harvard Forest falls readily into two distinct phases, a division that was made emphatic by a natural catastrophe of the first magnitude. From 1908 to the mid-1930's the general policy was sustained-yield management on a financially self-sufficient basis. Achievement of this goal depended largely upon the successful regeneration, without planting, of white pine, the most valuable species. On most of the upland area the attempts to regenerate pine failed. This became clear in the early 1930's, and in 1938 the residual pine stands blew down. Since 1938, then, forest management has been concerned largely with hardwood stands and with the coniferous plantations that survived the hurricane.

Within this 50-year time span, problems of site have become increasingly pressing. At the end of the old field white pine era, the general failure of the white pine regeneration experiments was related to the characteristics of the upland till soils (Lutz and Cline). Since 1938, a large amount of research has been devoted to various aspects of site, chiefly the surficial deposits. Yet at the time the Harvard Forest was established, little importance was attached to site variation in connection with the problem of natural regeneration of white pine. Nor, as was shown on pages 29 to 33, was site variation within broad limits considered by foresters and botanists of critical importance in the culture of white pine.

It is not within the scope of the present paper to examine the alternative goals of management open to the Harvard Forest staff in 1908. But within the frame of sustained-yield management dependent largely upon the natural regeneration of white pine, several different methods had been proposed by foresters and were available for consideration. Furthermore, a wide variety of ideas concerning white pine culture was in the literature.

The general aim of regeneration adopted at the Harvard Forest in 1908 was the reproduction, not the conversion, of the harvested stands. Thus, pure stands of white pine were to be replaced by pure stands of pine, as recommended by Lyford and Margolin; but hardwood stands and stands of mixed pine and hardwood were not to be replaced by pure pine.

Cutting systems were available in 1908 that were designed to insure the natural regeneration of stands. However, these were based upon the long experience of European foresters who worked with different species, and had not been tested in the United States. At this time the New England foresters were in general agreement that clear-cuts or modified clear-cuts in pure stands of white pine provided the best hope of successful regeneration of pine. This conclusion was based upon the silvical characteristics of pine, as they were known from field observations of existing wild stands, nursery experience, and a limited amount of experience derived from pine plantations.

The importance of seed source, the periodicity of seed years, and the seedbed requirements of white pine were well known and provided for in the cutting methods. Furthermore, the growth characteristics of the seedlings also were well known. For example, several studies of height growth in white pine had shown that total height growth was on the order of one foot during the first five years, and that the rate increased rapidly thereafter. But for the later years of a pine tree's life there existed no body of clinical experience, particularly in connection with pine trees growing in mixture with other species. Therefore, the early foresters were forced to resort to deductions from wild stands that contained pine trees.

The presence or absence of pine trees in the older wild stands was almost invariably explained in terms of pine seed source and the light requirements expressed in terms of relative shade tolerance of the various species. Most foresters believed that the rapid height growth of the older pine seedlings and saplings would assure their survival to maturity, and that the essential problem was the catch and successful germination of pine seed. Some advocated elimination of associated young hardwoods, where pine and hardwood occurred in mixture, with the idea of accelerating the growth of the pine or creating a greater density of pine. The absolute necessity of hardwood control in many areas was not recognized. The mushroom growth of the idea of shade tolerance had become a source of serious confusion.

This vagueness and conflict of opinion is understandable, indeed it was inevitable. Nature, with its many alternatives, had produced mature pine trees in all sorts of habitats. The importance of intricately related and chance circumstances that had permitted white pine to survive to maturity simply was not recognized. Furthermore, there was no way to evaluate the number of pine trees and pine stands that had failed to survive, much less why they had failed. The simple ideas of seed source explained the absence of pines too readily. The old field origin of the pure stands of white pine in New England and the existence of natural forest successions were well known, but their significance could not be realized fully until attempts to reproduce pine stands by natural regeneration methods had actually been carried out. The thought that natural processes had created forest stands that could not be duplicated by orderly cultural techniques, except at exorbitant cost, was not entertained. Furthermore, there was a spirit of adventure, a buoyant zest for a good cause, affecting the early foresters that was reflected in an unbounded optimism in measures of control over the course of stand development.

A tendency to study the silvics of American trees, one species at a time, without regard to the effects of adjacent trees of different species, was a source of additional difficulties. Thus, though many studies of height growth of young pines were made, comparative studies had not been made of young pines growing in mixture with other species — the rule in the wild stands. The significance of a most critical observation concerning the growth of young pines in mixture with hardwoods apparently was not realized by the observers (Pinchot and Graves), nor by other early foresters. Pinchot and Graves described 12–15-year-old pine trees on cutover land in Pennsylvania that had been suppressed or killed by overtopping hardwoods of sprout and seedling origin.

The first regeneration cuts in white pine stands at the Harvard Forest were initially successful. That is to say, pine reproduction in quantities sufficient to form a new pine stand was obtained. Within three years after the first cuttings, the serious nature of the hardwood competition was recognized. In fact, Tryon recommended that the new stand following the first shelterwood cut in the pure pine stand be managed as a hardwood stand, because the pine seedlings were so far overtopped by hardwood sprouts. By 1918 a comprehensive plan for control of the hardwoods by mechanical means had been presented (Fisher, 1918a), backed not only by data from the regeneration experiments but also by extensive field studies. Comparative studies of the height growth of young pines and the associated hardwoods had shown that early and perhaps repeated weedings were essential if the pines were not to be overtopped and suppressed or killed by the hardwoods. The intensity of the hardwood competition, and thus the intensity of weeding required, was found to vary with site characteristics. These site variations were partially defined in terms of soil characteristics.

The comparative measurements of height growth, in combination with the realization of the importance of the old field origin of the pure stands of white pine, clarified the mechanisms of the pine-hardwood successions described by botanists and early foresters (see pp. 25 to 29). Though the essential elements had been stated by Thoreau and Pinchot and Graves, the regeneration experiments drove the lesson home. Upon completion of these studies at the Harvard Forest, it was thought that control of the pine-hardwood succession by cultural means was biologically possible and economically feasible. Nevertheless, these studies gave the first clear sign that knowledge of site variation could provide a valuable tool in the establishment of young pine stands on cutover lands by natural regeneration.

By 1920 the regeneration goal in pure stands of white pine that grew on the heavier soils had shifted from the initial aim of reproduction to one of conversion to mixed pine and hardwood, as recommended by Spalding. In the early 1920's this was refined to an aim of mixed pine and hardwoods with the pines and hardwoods segregated within the stand. In 1925, the management goal was still further revised. The upland till soils were subdivided into two categories: medium and heavy. The heavy soils were characterized as hardwood sites where the culture of pine was not to be attempted, and the medium soils were characterized as sites where mixed stands of pine and hardwoods might be developed. At this time, an hypothesis was offered to explain the presence of the occasional white pines of high quality that are found in wild stands growing on heavy soils. Cline and Lockard believed that these single trees represented the sole survivors of a group of pines, whose numbers had been drastically reduced by natural processes during the life of the stand.

Within seventeen years, site characteristics had moved from a position of little or no importance in the management of the stands to a position where it was thought success or failure of the regeneration experiments depended upon the nature of the site. Furthermore, this success or failure was definable in absolute terms — pine or no pine — and not in the gentler phrases of site index reflecting height differentials. The change in position of site is even more striking because only one site factor, the nature of the soil materials, largely soil texture, was involved. Within the particular circumstances that obtained at the Harvard Forest (that is, within the frame of species composition, patterns of past land use, and financial structure), and with the use of the silvicultural techniques available at that time, knowledge of variations in the soil materials offered the most promising means of accomplishing the aim of white pine regeneration. In short, the outcome of the original plan of sustained-yield management hung upon a knowledge of the nature and distribution of soil variations.

It is therefore not surprising that research effort was channeled immediately into studies of the soil materials. But it is surprising that these efforts were turned toward providing proof that pure stands of white pine deplete the soil and prevent the establishment of a second crop of pure pine. These studies took the form of intensive comparative studies in the nutritional aspects of the upper parts of soil materials that supported pine stands and hardwood stands. Though these studies provided valuable information concerning the upper layers of the soil materials, they were of no value in untangling the problem of site recognition. Indeed, one of them denied that soil variation significantly affected the distribution of species.

In 1935, a comprehensive management plan for the volunteer hardwood stands that followed the cutting of old field white pine on upland till soils in central New England was proposed (McKinnon, Hyde, and Cline). This plan, as had that proposed by Cline and Lockard for the management of white pine, placed special emphasis upon soil characteristics as a basis for silvicultural decisions. Though the application of both of these general plans depended upon site recognition on the basis of soil characteristics, neither provided adequate morphological criteria for the identification of the soils categories.

Beginning in 1938, various aspects of the surficial deposits were studied in detail. Maps and descriptions of the deposits as seen by a glacial geologist (Upson, 1938) and a pedologist (Simmons, 1939, 1940, 1941) provided fundamental knowledge of this component of site. An important characteristic of the surficial deposits was overlooked until 1949, when Stout showed that firm layers present in the till, not shown by the soils maps, strongly affected the distribution of tree species. Since the completion of Stout's study, the characteristics and distribution of these firm layers, as well as their effects upon species composition and growth rates of the trees, have been studied intensively.

Since 1938 studies of past use of the land, microtopographic features, and microclimate have further broadened the knowledge of site components.

It is not possible to make a thorough evaluation of these detailed studies of site components at the present time. Some already have proved useful in the management of existing stands. Others have provided important leads for further silvicultural experiments and research. Others still constitute an available backlog of data that, at present, serves only to characterize the environment.

The Harvard Forest experiments in natural regeneration may be criticised on the grounds that the silvicultural treatments were too lightly applied. The fact that no pure stands of pine were developed on heavy till soils at all costs is to be regretted, both from the point of view of the research biologist and the research economist. However, from the point of view of forest production in our present market structure, the regeneration experiments on heavy till soils spelled out as only a long term experiment can the impossibility of growing pine on these sites using the then available silvicultural techniques. New techniques may change this picture. The suggestion has been advanced that the so-called silvicides have made it economically feasible to grow pine on the "hardwood sites" (Husch and Lyford, 1956). This has yet to be proved by bringing a stand of pine seedlings to commercial maturity on these sites. Still unknown are two critical items: 1) will silvicides produce pine stands on heavy till soils; and 2) if so, can their use be justified on economic grounds?

This review perhaps demonstrates the necessity of what might be called research in depth, if the practical goal of providing wood for the market at a modest profit is to be realized. Much of the grief connected with the white pine regeneration experiments at the Harvard Forest would have been avoided had the knowledge available in 1925 or 1949 been available prior to World War I. This last comment is absurd, of course. But foresters must ask themselves if they are engaged to the hilt at the present time in the job of obtaining fundamental information that may become critical twenty years hence.

Knowledge of site costs money. However, Harvard Forest experience suggests that the resulting knowledge decreases the amount of investment needed to bring stands of a desired composition to commercial maturity. Thus, knowledge of site components may enable the forest manager to use lower intensities of management to accomplish his aims. In extreme cases, such as that reviewed here, knowledge of site characteristics may make the difference between the flat failure of a policy and varying degrees of success.

Finally, the sequence of events reviewed here clearly demonstrates that the difference between site evaluation in terms of production rates and site evaluation in terms of stand establishment can be critical wherever intensive management is attempted through more than one rotation.

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