This is to certify that the

thesis entitled

FACTORS AFFECTING JACK PINE REGENERATION

ON THE SAND PLAINS OF NORTHERN LOWER MICHIGAN

presented by

John David Marshall

has been accepted towards fulfillment
of the requirements for

M.S. degree in Forestry

James B Hart Jr
Major professor

Date 11-14-80

O-7639

FACTORS AFFECTING JACK PINE REGENERATION ON THE SAND PLAINS OF NORTHERN LOWER MICHIGAN

By

John David Marshall

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Forestry

1980

ABSTRACT

FACTORS AFFECTING JACK PINE REGENERATION ON THE
SAND PLAINS OF NORTHERN LOWER MICHIGAN

By

John David Marshall

Factors exercising greatest control over success of planting and natural regeneration techniques were identified. Seedling stocking was related to physical and chemical soil properties and to understory and overstory vegetation.

Partial cut areas studied included shelterwood, seed tree, and strip cut areas. Seedling stocking averaged 1346 trees/hectare. Seedling numbers were positively related to bearberry and sweet-fern cover, and inversely related to overstory basal area and several measures of B horizon fertility.

Burned areas studied included prescribed burns and wildfires through standing trees. Seedling stocking averaged 7123 trees/hectare. Regeneration was inversely related to sedge cover and depth to mottling and positively related to bearberry cover, pre-fire stand density, and soil profile thickness. Post-fire seedling establishment was found to reach a maximum two to five years after burning.

An average of 75.4% survival was found on the plantations, with no significant differences among the site types studied.

ACKNOWLEDGMENTS

I would like to express my gratitude to my major professor, Dr. J. B. Hart, for his invaluable advice and help in the design, administration, and writing of this study. I would also like to thank the other members of my graduate committee, Dr. D. I. Dickmann and Dr. G. Lemme, for their advice and encouragement. Thanks are also due to Drs. D. Mokma and C. Ramm for their assistance in the design and analysis of this study.

I am thankful to the Forest Management Division of the Michigan Department of Natural Resources for funding this research and for their assistance in the location of study areas. The cooperation of the Wildlife Division is also appreciated. Thanks also go to the Department of Forestry and to the U.S. Forest Service for the use of their laboratory space and equipment.

I am grateful to Jackie Myrold, for the care with which she supervised the soil analysis. My appreciation also goes to Don Dekker, Paul Doescher, Bart Hoag, John LaLonde, Pat McMullin, Dennis Pawl, Dan Stouffer, and Tom Nutt, who at various times were responsible for much of the data collection and analysis.

Finally, I owe great thanks to my wife, Beth, for her help in preparing this manuscript and especially for her uncomplaining encouragement during the last harried month of its preparation.

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

The importance of jack pine[1] has steadily increased in the Lake States since the turn of the century. Once regarded as a weed tree, the introduction of the sulphate process has made it one of the most desired pulp species. Stumpage prices have recently risen sharply due to the short supply of softwood fiber. This softwood shortage is expected to continue into the near future, due to the difficulty of establishing conifer stands in this region.

Jack pine is also highly valued by wildlife managers because of its essential role in the life cycle of the Kirtland's Warbler. This endangered species nests only in stands of dense young jack pine. The warbler's numbers have decreased since the advent of fire control.

Regeneration of jack pine has long been a problem. Clearcuts nearly always fail to regenerate without additional treatment, and what little regeneration does appear is usually of low-value hardwoods. During the 1930s, large acreages of jack pine were planted by federal work programs. Once these programs were dismantled, however, the high cost of planting forced foresters to find less expensive means of regenerating this species, including various kinds of partial cuts, prescribed burns, broadcast seeding, and direct seeding.

---

[1]Scientific names of species encountered in this study are listed in Appendix A.

This study was designed to identify the site factors controlling the regeneration success of burns, partial cuts, and plantations on the outwash sand plains of the Grayling-Roscommon area in northern lower Michigan. These sites, which are extensive in the area, had been identified as being particularly difficult to regenerate. It was believed that once the controlling factors on these sites were identified, site preparation techniques might be adjusted or changed to deal with them.

A secondary objective of this study was the development of criteria to be used to decide which of the various regeneration techniques to use on a given harvested area. These criteria were to be developed as guidelines to be used by field foresters.

LITERATURE REVIEW

The literature on jack pine is very extensive. To make it more understandable, this review is divided into ecology and silviculture. The jack pine ecology section considers the characteristics of the species, more or less independent of management. The jack pine silviculture section considers the various techniques used in the management of this species. Both these sections emphasize regeneration. A final section, soil properties on burned jack pine sites, deals with the effects of burning on the dry, infertile, sandy soils typically occupied by jack pine.

Jack Pine Ecology

The ecology of jack pine is an extremely interesting subject, due in large part to its dependence on fire and its ability to occupy the driest, least fertile sites available. This section of the literature review concerns itself with the characteristics of this species, including the role it plays in the ecosystem and the adaptations allowing it to fulfill that role. This includes its distribution, history, genetic variability, seed dispersal, germination, seedling development, successional role, associated species, and productivity.

Distribution and History

Jack pine is a short-lived, small to medium tree with the most northerly and one of the most extensive ranges of any of the North

American pines (35). Found throughout the northern Lake States, it is common or abundant in central Michigan, central Wisconsin, along sand dunes bordering Lake Michigan, and north and west of Lake Superior (78). Commercial stands in the U.S. are restricted to the Lake States (47).

Jack pine grows in areas with cool to warm summers, very cold winters, and low rainfall. Across the majority of its range, annual precipitation varies from 15 to 35 inches,[2] and the annual frost-free period lasts from 80 to 120 days (34, 35, 78). Summer droughts commonly occur in the Lake States and through the western part of the range (78).

One of the unique features of this species is its ability to grow on very dry and infertile soils incapable of supporting almost any other tree species in this region (35, 36). These soils are often coarse or medium sands, gravelly soils, or shallow soils underlain by bedrock (35, 36). Fine sands, sandy loams, loams, and clay loams may also support jack pine stands, although severe disturbance is usually required for establishment on these finer-textured soils (35, 36, 79). It is found only rarely on poorly drained soils (35, 79).

During the last glaciation, jack pine was apparently found in an extensive glacial refugium in the central Appalachians (35, 81). The species moved north and west behind the glaciers as they receded (13). Pollen analysis in northern Minnesota bogs has shown that jack pine became abundant in that area about 9,000-10,000 years ago (13).

---

[2]All data originally reported in English units of measurement will be similarly reported in this review. See Appendix B for English-metric conversions.

Charcoal is also present in these peat layers, indicating that fires were occasionally sweeping through this area at about the same time (13, 92). Soil development and vegetative succession in the ensuing time have apparently restricted the species to those areas too dry or too frequently burned for the more demanding species belonging to later successional stages. That fire frequency and poor soils control jack pine distribution is also suggested by reports from a botanical expedition that crossed the northern lower peninsula of Michigan in 1888. They found extensive stands of even-aged jack pine on the sand plains. Evidence of fire was always present in these stands (98).

Utilization of the species was rather poor during the logging of the old-growth red and white pine stands in the late nineteenth century because of the high merchantability standards of the time. The intense slash fires that followed this logging killed the few remaining red and white pine seed trees and regeneration and created nearly ideal conditions for dispersal and germination of jack pine seed (36, 48). Following these fires, jack pine became dominant on many sites on which it had formerly been only a minor species (36). As the second-growth stands matured, the value of the species increased, better utilization began to occur, and regeneration of the species became a problem (45, 46, 47, 48, 58, 94).

Genetic Variability

Genetic variability within this species tends to be clinal through the western part of the range because stands are often contiguous and selection has been primarily in response to climate. In the extreme eastern range the disjunct populations show more random variability (35). Populations from the Lake States (including all of Michigan except the eastern upper peninsula) tend to be taller, broader-crowned, more frequently serotinous, and lower in cone production than the average for the species (51). In general, provenances from the northern lower peninsula seem to be the fastest growing, while the more northern provenances (including those from the upper peninsula) tend to be slower growing and more frost hardy (35, 51, 80). Arend et al. described four ecotypes in the Lake States. The ecotype from the western lower peninsula of Michigan was the fastest growing, that from the eastern lower peninsula was second fastest, the Minnesota and Wisconsin ecotypes were variable, but generally below those from Michigan's lower peninsula, and the upper peninsula ecotype was the slowest growing (20). Genetic variability has been shown to exist in susceptibility to the sawfly, the jack pine budworm, and pine-oak rust (20, 79, 80). Lodgepole pine is a closely related serotinous species found in the Rockies and known to hybridize with jack pine where their ranges overlap (61).

Seed Dispersal

Cameron (29) describes the serotinous nature of the cones of jack pine. Serotiny refers to the cones' ability to hold the seed beyond ripening. The cones are sealed by a vapor-resistant resinous material at the tip of the cone scales. A temperature of at least 50°C (122°F) will soften this resinous material, allowing the cones to open. Higher temperatures will open the cones more rapidly. Once the resin has softened, exposure to low relative humidity will reflex the cone scales, releasing the seed. The cones do not reclose upon being returned to higher humidities.

The closed cones have very low heat conductivity, which protects the seed held inside when the cone is exposed to heat (29). Thus in a fire, the seed survives even though the parent tree is killed, unless temperatures are high enough for a sufficient time to cause cone ignition and destruction of the seed (36, 48). The ungerminated exposed seed is rather heat tolerant also, as it will not be killed until it is exposed to a temperature high enough to ash the wing and crack the seed coat (29).

Cone serotiny varies genetically (48, 81). Nonserotinous cones are more common from seed sources from the southern portion of jack pine's range (48). Serotiny is also dependent on age and on stand density (35). In mature stands in Saskatchewan, 10% of the cones were open, while almost all ripe cones on 7- to 10-year-old, open-grown trees were open (35). Laboratory tests comparing cones from trees less than 10 feet in height to trees greater than 10 feet in height under identical temperature and humidity conditions showed the cones from the smaller and younger trees were more easily opened (54). Another study in Manitoba showed that 20-year-old stands annually dispersed approximately 36,750 seeds per acre, over four times the amount dispersed in 40- and 60-year-old stands (35). Seedfall in open stands often exceeds that in dense stands (35, 48).

Serotinous jack pine stands are able to store many years' production of seed. Seeds may be locked inside the cones for up to

25 years (24). Stored seed crops have been reported from "several pounds" (36), to 12.9 and 13.5 pounds per acre (48). Other studies have reported 1,540,000 seeds per acre in southeastern Manitoba and from 6,000,000 to 8,000,000 per acre in a mature stand in Ontario (35), and up to 9,000,000 seeds per acre in Michigan (46). Some studies indicate that the viability of this older, stored seed tends to be somewhat lower than recently ripened seed (25, 46), while other studies have shown no effect (48, 71). Older seed may also be somewhat slower to germinate (35). Most researchers have concluded that viability is high enough to make a significant contribution (25, 46, 48, 77).

Seedfall may begin almost immediately after a fire and may be completed in as little as 3 to 15 days, depending on fire intensity, air temperature, and humidity (26, 46, 48). Seedfall from logging slash may take two or more years, usually being highest during the hot, dry periods of mid-summer (35, 47). Rodents, grackles, blackbirds, robins, and other birds have been reported to eat large amounts of seed (48).

Germination

Dispersal of large amounts of viable seed is the first requirement for regeneration. The seed must also fall on a seedbed able to provide the conditions necessary for germination (22, 58). Seedbed moisture levels are probably the most common factor limiting germination (21). The seed, released from the cone at a moisture content of 12-15%, must absorb enough water to reach at least 53-54% moisture content before it will begin to germinate (29). Seedbed moisture levels are dependent upon the amount and distribution of rainfall, shading, evaporation rate, depth to the water table, soil texture, seed covering, season of dispersal, seedbed type, and competing vegetation (5, 21, 22, 35, 36, 38, 39, 50, 54, 57, 58, 87, 95).

The factor most important in controlling seedbed moisture is seedbed type. Mineral soil and humus serve as the most favorable seedbed types for jack pine, and deep undisturbed litter serves as the poorest (5, 35, 36, 48, 57). This is partially due to the low heat conductivity of dry litter, which results in higher maximum surface temperatures than on mineral soil. Litter is also less able to provide the moisture needed by the germinating seed because much of the water it absorbs is held within the cellulose fibers rather than on the surface of the particles, as in mineral soil and humus. Also, the textures of mineral soil and humus tend to be finer, allowing closer packing around the seed, so that capillarity may keep up a steady water supply to the seed during imbibition (21, 48, 57). Shallower litter layers may improve regeneration by allowing the seedling easier access to the mineral soil below (39). A thin (less than 0.5 inch) soil covering may also improve germination (50).

Temperature conditions can control germination. One study (19) has shown that field germination begins whenever daily maximum air temperatures exceed 64°F (18°C). Eyre and Lebarron (48) found that field germination occurred when the 10-day mean maximum temperature was greater than 65°F (18°C). Germination under controlled conditions was found by Ackerman and Farrar (15) to be three days slower at constant temperatures of 60°F (16°C) than at various combinations of 60°F (16°C), 70°F (21°C), and 80°F (27°C) over 24-hour periods.

Light exposure also controls germination since jack pine seed has a minimum light exposure requirement of two to four minutes to break seed dormancy. This light exposure will not break dormancy unless the moisture content of the seed is greater than 10 to 20% by weight. This breaking of dormancy is not reliable at temperatures below 60°F (16°C) (2).

Jack pine seed viability is usually above 70% (5, 35, 67, 71) with lower values due to inferior cleaning techniques, to seed not given its light requirement, or to slower germination of older seed (2, 25, 35). Seeds exposed to fire have been shown to germinate better than unburned seed (5, 71).

In a normal growing season in Manitoba, germination begins as early as mid-May and ends, in most cases, by the end of June, with sporadic germination through the rest of the summer (35, 71). However, this generalized germination pattern is seldom described in case studies, because while the seed of most conifer species germinates the spring following ripening, jack pine seed germinates whenever conditions are suitable (3). For this reason and because of the slower or less complete germination of older seed, reports of 99% germination (32) are interspersed with findings of much lower first-year germination percentages (25, 35). Beaufait (26), studying post-fire jack pine regeneration, describes "apparent dormancy" of seed resulting in large numbers of germinants in the second and third growing seasons.

Seedling Development

Jack pine seedlings are particularly vulnerable to mortality during the first growing season following germination (5, 57). One study found that, of the seedlings germinating the spring after a fire, 75% survived June, 56% survived July, and 42% survived August, with 38% surviving through the end of the second growing season.

The succulent first-year seedlings are especially susceptible to heat and drought injury (16, 21, 32, 35, 48, 57, 63, 87). A temperature of 49°C (120°F) is considered lethal for first-year seedlings (87). Another study reports that temperatures in excess of 122°F (50°C) for more than two hours will cause injury (48). Heat and drought injury are more likely to occur on dry, sandy sites and near midsummer (18, 32, 35, 87). Dry sites may be higher risks because of the lack of shade cover (48) and because surface soil moisture is not available to evaporate and cool the site (21). Removal of litter, shading, and early spring germination reduce the temperatures to which newly germinated seedlings are exposed (6, 21, 39, 48, 59, 67, 79). Other major causes of mortality include herbivores (35, 48, 57), damping-off fungi (especially under deep slash piles) (54), and high salt concentrations from ash and from charcoal (5, 93).

Jack pine grows relatively slowly during its first three to four years (5, 35). During this period a taproot develops to about 50 cm in length and penetrates below sod competition and possibly into a good source of water and nutrients (35), often a spodic horizon (85). After approximately four years, lateral root growth in the A horizons becomes dominant over taproot growth. At this time, the seedling begins to grow very quickly and the top:root ratio rapidly increases (35). Interestingly, jack pine growth is greatest with less than full sunlight for the first four years, after which time 100% sunlight becomes optimal (59).

Early growth rates are much higher on mineral soil and burned seedbeds than on undisturbed litter (54). Competition and water availability influence growth rates at this stage, with best growth on a site dry enough to support less vigorous competition and yet moist enough for rapid jack pine growth (35, 88). However, moister sites have better growth rates after crown closure (37).

According to Rudolf (79), the most common causes of mortality in established seedlings older than age one are heat, drought, and competition. Herbivores (35, 48, 77) and deformed roots in planted trees (77) are also important. Heat is most damaging to smaller trees (77), with little mortality in trees greater than 1/2 inch in diameter (16). Heat damage on small trees can be identified by a layer of discolored cambium just above the soil surface (16). Heat often predisposes seedlings to drought damage and vice versa (16, 87).

Successional Role and Associated Species

Jack pine is commonly recognized as a fire species because its silvical characteristics make it "ideally suited to regenerating after wildfire" (36). The advantages of cone serotiny on frequently burned sites, discussed earlier, and the beneficial effects of burning on seedbed conditions explain the common occurrence of this species in pure or nearly pure even-aged stands throughout most of its range (35, 36, 48).

Jack pine is able to function as a pioneer species most effectively on dry, infertile sites. Wilde (102) found it to have the lowest nutrient requirements of any of the Lakes States conifers. Its drought resistance was demonstrated by Pereira and Kozlowski (74), who found that, relative to red pine, jack pine stomates close rapidly in response to soil water depletion. Its internal resistance to water flow is also relatively high (74). Because of these and possibly other adaptations, jack pine is able to survive on coarse sands and shallow outcrop soils, where conservation of moisture is a necessity, and where few other tree species can survive, except in the understory.

The individuals of species commonly occurring in association with jack pine must have means of surviving frequent fires. Ahlgren (10) found that the majority of plants reproducing after a fire in northeastern Minnesota were of vegetative origin. Darlington (42) found that 95% of the common plants of the jack pine plains of Michigan were perennials with deep roots or rootstocks adapted to severe conditions of drought or of surface burning. For example, bracken fern, the blueberries, and aspen survive a fire predominantly by underground structures which sprout following a fire (10). Ahlgren (8, 9) found that the grasses and sedges, and many other post-disturbance pioneer species, become much more common and produce a great deal of seed after the removal of an understory. This seed is stored in the forest floor and germinates at the time of the next disturbance.

In the boreal forest region, which is north of the study area, jack pine is commonly associated with trembling aspen, paper birch, white spruce, black spruce, and balsam fir (36, 48). It is succeeded by a mixture of spruce and fir on all but the driest of sites. Pure or almost pure jack pine stands can be found on thin soils overlying rock outcrops; on glaciofluvial plains, eskers, and kames with sandy and gravelly soils; on fluvial sand terrances along rivers; on sand dunes; and on upland sandy and loamy tills. It occasionally occurs on lowlands of all textures (37). On better sites with silty sands, loamy sands, and loams, jack pine is often mixed with varying proportions of trembling aspen and white birch (37). Black spruce frequently forms an understory on rocky upland tills and in depressions on low-lying flats (37). White spruce and balsam fir are commonly found in the understory on all soils (37).

In the Lake States, common associates include those listed above as well as northern pin oak, bur oak, red pine, and eastern white pine. In this region jack pine is found primarily on sandy sites, and may be replaced by red and white pine, followed by a mixture of hardwoods dominated by sugar maple, basswood, and northern red oak (48). Cayford et al. (35) suggest that the red and white pine stage is succeeded by a spruce-fir mixture in the Lake States. In north-eastern Minnesota, where jack pine is found on finer-textured soils as well as sandy soils, jack pine may also be succeeded by a dense undergrowth of alder, hazel, and beaked hazel, which is gradually replaced by a spruce-fir mixture (87).

The Canadians have classified the moisture regimes of different jack pine sites based on understory vegetation. Table 1 gives a general summary of this system (adapted from 35). Chrosciewicz (37) found that the water table remained below seven feet throughout the year on the dry and very dry sandy sites, but in the fresh and moister than fresh sands, the depth to ground water varied between three and six feet.

Table 1. Understory species characteristic of various soil moisture regimes

Moisture Regime	Characteristic Species
Very dry	Reindeer lichen
Dry	Bearberry, Blueberry spp., and Wintergreen
Fresh	Twinflower, False lily-of-the-valley, Bunchberry, Bracken fern, and scattered shrubs
Moist	Labrador-tea, Leatherleaf, and Raspberry

Using the Canadian system as a starting point, it is apparent that a majority of the sites studied by Ahlgren (5, 6) in northeastern Minnesota are fresh or moist, as evidenced by the predominance of bunchberry, labrador-tea, bracken fern, raspberry, false lily-of-the-valley, twinflower, and many shrubs. In contrast, Beaufait (24) found a dry portion of an outwash plain in northern Michigan to be dominated by bearberry, blueberries, bracken fern, and lichens, among other species indicative of drier conditions. Thus, where site descriptions in a study are incomplete, one can predict the character of the site by examining the understory vegetation. Also, this points out the fact that all jack pine sites are not alike and caution must be used in extrapolating research results from other regions.

Productivity

Pawluk and Arneman (73), working in northeastern Minnesota and northwestern Wisconsin, concluded that fertility and especially water-holding capacity were important determinants of site quality as measured by site index. They used regression analyses to relate jack pine site index to various site factors in eight soil series with textures ranging from sandy loams to sands. They found highly significant curvilinear relationships between site index at 50 years and texture, with site index increasing as the sum of the percentages of very fine sand, silt, and clay of the A2 and B horizons increased. They also found a curvilinear relationship between site index and the available moisture capacity of the Aoo, A2, B2, and B3 horizons, with higher moisture capacities increasing site productivity. Significant linear relationships were found between site index and the total exchange capacity of the A2, B2, and B3 horizons, exchangeable potassium of the A2, B2, and B3 horizons, and the percent base saturation of the Aoo, Ao, A2, and B2 horizons with increases in any of these variables causing an increase in site index.

Wilde et al. (103), working in jack pine plantations throughout the state of Wisconsin, related site quality in terms of average annual growth to physical and chemical soil properties of the surface six inches. They found that nearly all low-quality sites, which they defined as those with less than 13 inches of average annual height growth or site indices less than 53 feet, were deficient in at least one nutrient. They found the height to age ratio to be most strongly determined by organic matter content, followed by available phosphorus, silt plus clay content, and available potassium. Wilde (102) then published minimum levels of pH, % silt plus clay, % organic matter, exchange capacity, total nitrogen, available phosphorus, available potassium, exchangeable magnesium, and exchangeable calcium for a site with a site index of 53 feet.

Jameson (55) and Chrosciewicz (37) have related jack pine productivity to the Canadian system of classifying moisture regimes. Jameson developed site index curves for the various moisture regimes on fresh tills through very dry dune sands. He found the average site index on dry sands, the site type most similar to the Grayling sand (typic Udipsamment, mixed, frigid) to be 48 feet.

Chrosciewicz (37) looked at pure or almost pure jack pine on deep siliceous very fine sands, fine sands, and medium sands and examined the effects of higher percentages of basic rock particles in the sands. He found that site indices were highest on moist sites, decreasing on wetter sites and on fresh sites, lower still on dry sites, and lowest on very dry sites. He also found that site indices decreased in going from very fine sands to fine sands, and from fine sands to medium sands. Sands with 30 to 40% basic intrusive and effusive rock particles also had higher site indices than sands with less than 10% basic rock particles. The effects of texture and basic particles were especially evident on the drier sites. Climatic region was also shown to have a significant effect on site productivity. With few exceptions, the same results were found for diameter growth.

Bensend (21) found that jack pine seedlings showed greatest height and weight with soil nitrogen concentrations of 200 to 250 ppm. Root weight increased as concentrations increased to 100 ppm, beyond which there was little change. Seedlings grown under optimum conditions were as drought resistant as those grown on deficient soils.

Jack Pine Silviculture

Jack pine regeneration has been a problem for foresters for some time (35, 48). This species lacks the sprouting ability that makes aspen regeneration easy to obtain. Yet, it does not regenerate as poorly as red and white pine (7). In fact, it regenerates very well just often enough to allow foresters and wildlife managers to believe that obtaining natural regeneration should be a fairly simple task once some reliable technique can be found. The following sections will review the major natural and artificial regeneration methods that have been attempted and discuss their risks, advantages, and disadvantages.

Site Preparation

The success of both seeding and planting is highly dependent on site preparation (41, 57, 58, 78). Site preparation involves the management of site factors associated with soils, vegetation, and slash. Rudolf (78) goes as far as to say, "Generally speaking, field planting without some sort of site preparation is merely so much wasted effort." At least two to three years of freedom from severe competition are needed for seedling establishment (78). This is especially important on dry sites (35, 87).

Furrowing and scalping are two methods commonly used to provide the conditions needed for seedling survival (34, 76, 78, 98). Furrowing usually provides for faster growth (22) and better survival than scalping (54, 87). Furrowing should be just deep enough to turn back the surface root mat (36). Machinery used includes front-mounted equipment, such as the V-blade, and pulled equipment, including fireline plows and disks (36). The Athens disk is often recommended for use on coarse-textured soils (35, 41, 46).

Burning is also used for site preparation. It can be useful for slash reduction, which reduces planting costs and fire hazards (3, 97). In many cases, however, the primary purpose of prescribed burning is to reduce the depth of the surface organic horizons prior to seeding (35, 38). These seedbed improvement burns must take place under dry conditions to bring about sufficient litter reduction (35, 38, 39, 97). The subsequent seeding is most successful on those microsites having the shallowest litter depth (5, 35, 39, 54, 97). The maximum litter depth considered a "high quality seedbed" is 0.5 inches (39). This litter reduction must also occur when burning slash under seed trees (26, 35).

Mechanical site preparation is presently more common than the use of fire (36). The advantages of mechanical site preparation include that it can be done almost independent of weather conditions, it is less labor-intensive, and it is less risky than burning (36). Some of these same advantages apply to the use of herbicides, which have been shown to improve growth and survival of red pine on dry sandy sites in Wisconsin (56).

Seeding Techniques

The least expensive methods of regenerating logged jack pine stands involve the dispersal of seed across the area (48). The techniques used to accomplish this may involve dispersal of slash containing seed, seed produced and released from nonserotinous overstories, seed released by slash burning under serotinous seed trees, or seed brought in from off the site and dispersed by ground or aerial application methods.

Clearcuts on which the slash is untreated or windrowed almost always fail to restock sufficiently, despite the large amount of viable seed frequently left in cones in the slash (30, 33, 35, 48). The germination failures are due largely to poor seed dispersal and poor seedbed conditions (11, 48). Seed is released from windrowed slash only on the outside edges of the slash piles because the serotinous cones inside the piles are shaded from solar heating (48). Cones in untreated slash seldom open because air temperatures above ground level seldom reach the levels needed to open the cones (48). What seeds are released are not likely to germinate and survive because conventional logging leaves litter layers intact on most of the area (48).

Eyre and LeBarron (48) suggested site preparation followed by lopping and scattering of the slash. The lopping of slash puts the slash in closer proximity to the soil surface, where temperatures are more likely to be high enough to open the serotinous cones (22, 54, 71, 75). Noakes (44) found that in lopped and scattered slash, many cones within one foot of the ground had opened, fewer had opened at a height of three feet, and very few had opened more than three feet above the soil surface. Another study found that nearly all seed released was from cones within seven inches of the surface (35). Ground scarification is absolutely essential to the success of this treatment (22, 35, 58, 75). A minimum of 60% of the area must be scarified (75). Jameson (41) reports that this method works in Saskatchewan, even on dry sites, and it is recommended for nutritionally poor, dry, and very dry sites in Manitoba (33). In general, however, this method has not been widely used, due to the inevitable failures where it was misused, but also because of the high labor costs involved relative to the low productivity of the sites (26). It should also be noted that the minimum temperatures necessary for cone opening are also lethal temperatures for first-year jack pine seedlings (25, 48, 87).

Broadcast seeding has also been used with extremely variable results (33, 35, 41, 48). Adequate seedbed preparation and favorable weather conditions are necessary for success (35, 41, 79). Some successes in improving numbers of seedlings have been reported, although a high proportion of failures have also been reported, and in many cases those trials labeled successes were far below optimum stocking. Cooley (41) reports on a successful seeding attempt on a Grayling sand site in northern lower Michigan, but the study may have been conducted during an unusually wet growing season (personal comm., 1979). In general, seeding is not recommended in the Lake States except where soils are fine-textured or where the water table is permanently within two to five feet of the surface (48, 79).

Spot seeding involves the placement of seed into a scalp or a furrow. Although results are extremely variable, this method may be successful if the seed is planted in sufficiently large mineral soil scalps or furrows, and if the weather allows for germination and initial survival. Sowing at depths of 0.25 to 0.75 inches improves results (35, 50). Some tentative successes have also been achieved in Manitoba with a corn seeder planting in furrows behind a V-blade (33, 35).

Burning of slash under seed trees has been recommended as another method of obtaining regeneration (26, 32, 35, 36, 48). It has been successful in Saskatchewan in a 70-year-old stand where 60 trees per acre were left (35), in Manitoba where 20 dominants and 150 unmerchantable one- to three-inch trees per acre were left (35), and in Minnesota where 10 seed trees per acre averaging 12 inches d.b.h. yielded 15,000 to 20,000 seedlings per acre (36). Beaufait (26), working in the northern lower peninsula of Michigan, found that slash burning under 12 to 50 seed trees per acre under dry conditions usually yielded sufficient seed and litter reduction to regenerate stands. Slash burning cannot be expected to release live seed from the slash itself, however. The slash carrying the fire nearly always ignites the cones it contains, killing the seed (26, 35, 48). The seed regenerating the stand must come from cones in the overstory. Beaufait (26) concluded that the number of seed trees to be left depended on the number and position of the cones. This slash-burning method should only be applied in stands with greater than 100 square feet of basal area, yielding at least 18 inches of evenly distributed slash, on areas greater than 10 acres in size, in areas not near other flammable stands, and with a minimum of 12 good trees per acre left as seed trees (26). Generally this method is more successful as more seed trees are left (32). Failures using this method have also been reported (35, 48).

Shelterwood cutting methods have been used with jack pine in the northern lower peninsula for the past 20 years. Caveney (31) found jack pine stocking on shelterwoods to be closely related to residual basal area of jack pine, residual basal area of open-coned trees, residual basal area of white pine, residual basal area of aspen, and basal area of recent mortality. The average stocking in his study was 36% of mil-acres stocked with jack pine, or 754 jack pine seedlings per acre. The average stocking on Grayling sand, the most heavily sampled soil series, was 37% of mil-acres stocked. Much better stocking occurred on sites with ground cover less than six inches in height. On those sites dominated by reindeer lichen, 76% of mil-acres were stocked. Stocking generally improved with time since first cutting. An advantage of this method is that it is aesthetically pleasing throughout the regeneration phase (31). Disadvantages include the cost, harvesting an area twice, and the creation of ideal conditions for the jack pine budworm (31). In Minnesota, shelterwood cuts have not been successful in obtaining adequate regeneration (48). Neither seed tree nor strip cuts regenerated well in Manitoba, presumably because of poor seedbed conditions (35).

Planting Techniques

Planting is the most reliable regeneration technique, but it is also more expensive (26, 48). Several studies suggest planting in furrows for dry, sandy sites in Canada and in northern Michigan (26, 33, 35, 87). The advantage of planting is that it circumvents the germination and first-year survival problems so common on dry, sandy sites (26, 33, 35, 87). The planted seedling has a well-developed root system placed immediately into a relatively stable source of moisture. It also is likely to be more heat-resistant than the new germinant (87). Studies with jack pine and red pine have shown that larger, sturdier, and older stock nearly always outperforms smaller seedlings (17, 48, 69, 76). In one study, planted 2-1 jack pine averaged 10 feet higher in site index than plantations of 2-0 stock (69).

Fall planting is not recommended on finer textures because of the possibility of frost heaving (48). On sandy soils, Rudolf (79) has shown that spring plantings have higher survival. Eyre and LeBarron (87) concur, attributing the poorer survival of fall plantings to insufficient hardening off of seedlings and poor root contact due to root dormancy. However, fall planting was a common practice in the Lake States in the past (76), and if lower survival can be tolerated or compensated for by planting more seedlings, the extension of the planting season may make fall planting worthwhile.

Partial shading has been shown to improve first-year survival, probably because of lowered transpiration rates (18, 60, 77). However, this overstory must later be removed for best development (18).

Jack pine has also been experimentally planted in tubes and in Jiffy peat pots on Grayling sands. Success has been shown to depend on shade and on watering regime (67, 68).

Two final points applying to any silvicultural prescription should be made. First, prompt regeneration of cutover stands is easier and more likely to be successful than allowing several years to pass before regeneration is attempted (35, 57). Second, no silvicultural treatment utilizing seed from the existing stand should be prescribed without consideration of the relative numbers of serotinous and nonserotinous cones on the trees in the stand (31, 57).

Soil Properties of Burned Jack Pine Sites

Generalities are hard to draw regarding the effects of fire on soils. The effects are highly variable, being a function of such things as region, climate, forest association, soil type, plant species, and fire intensity (10, 99). This section will briefly review the literature on fire effects, with emphasis on those aspects most pertinent to jack pine regeneration, and also emphasizing studies conducted on sites similar to the sand plains on northern lower Michigan. For additional reviews the reader is referred to Wells et al. (99) and especially to Ahlgren and Ahlgren (10).

This section of the review is based largely on two studies. The first is by D. W. Smith (89), in which he studied nutrient dynamics over a 17-month period immediately after a severe fire. The site was a well-drained sandy podzol on an outwash plain in Ontario dominated by jack pine. The second study on which this section is based is a Master's Thesis by D. G. Scholl (82), in which he compares soil properties on a prescribed burned to those on an adjacent unburned site on a Grayling sand in Delta County in upper Michigan.

The effects of burning on soil organic matter are extremely important because large losses of soil organic matter might often result in lowered site productivity, especially on the coarser-textured soils (103). The soil organic matter includes the surface layers referred to as the O horizon, forest floor, litter or duff, and the organic material incorporated into the mineral soil. Smith (89) found that 79-91% of the organic matter in the L-F-H horizons was consumed in a hot fire. Scholl (82) found that an average of 72% of the organic matter in the O horizon (L-F-H) was consumed. Smith (89) reported that the percentage of organic matter between depths of 0 and 2 cm in the mineral soil was decreased for three months, then rose to above pre-burn levels after snowmelt the following spring. The organic matter contents in the deeper mineral horizons were unchanged for three months, after which they increased. Organic matter losses are usually restricted to the organic horizons and the upper inch of mineral soil, the losses decreasing with depth (10, 12, 82, 89, 99). Frequent burning, rather than causing an absolute loss of organic matter, causes a redistribution from the forest floor into the upper mineral horizons (10, 12).

Fire usually increases soil pH, although the persistence, depth, and degree of effect vary (10, 99). The amount of the increase depends on the amount of ash released, the original soil pH, the chemical composition of the ash, and the wetness of the climate (99). The increase is often closely related to the amount of calcium released in the ash (99). Smith (89) found large pH increases in the L-F-H horizons four days after a fire. He found the pH's remained high for 10 months, then began to approach pre-burn levels. Fifteen months after burning, pH's were at or below pre-burn levels. The pH's in the mineral soil horizons increased slightly as those in the organic horizons decreased.

Smith (89) reported conductivity, associated with higher salt-electrolyte concentrations, to be sharply increased in the L-F-H horizons four days after burning, but it decreased rapidly between five weeks and three months after the fire. As the conductivity of the surface horizons decreased, that of the deeper mineral horizons increased, especially in the first spring following the fire. Within 15 months, conductivities were near or below pre-burn levels.

The calcium contained in the L-F-H horizons in Smith's study (89) was predominantly in acid-extractable forms prior to burning. Following the burn, there was a sharp increase in water-soluble forms, and then a decrease to below pre-burn levels within 15 months. Calcium contents increased throughout the deeper mineral horizons, with the increase in water-soluble forms between 2 and 12 cm especially noticeable. After 15 months, the mineral soil horizons were near pre-burn levels. In general, calcium concentrations change as described above, increasing due to increased mineralization and then decreasing as some leaching and redistribution takes place (23). Scholl, sampling 17 months after a burn, found much more variable calcium concentrations on burned plots than on unburned plots in the O and Bir horizons. The concentration differences were not significantly different, however (82). The rate of leaching of calcium relative to that of other cations on these sites has been described as high (4) and as low (12, 89).

Magnesium concentrations have been shown to increase immediately after burning and then to decrease (4, 97). Magnesium concentrations at one-meter depths were found to be higher two months after fire than before it. However, because these concentrations were lower than those at 20 cm, Adams and Boyle (4) concluded the subsoil was retaining magnesium. Scholl detected significantly higher post-burn magnesium concentrations only in the O horizon (82).

The concentrations of potassium, especially the water-soluble forms, were shown to increase sharply in the L-F-H horizons immediately after burning in Smith's study (89). The concentrations then decreased sharply within five weeks, with the water-soluble forms decreasing most rapidly (89). Ahlgren and Ahlgren (10) also note this tendency for a sharp increase, followed by rapid leaching. Scholl, sampling 17 months after the fire, found no significant differences (82).

Extractable phosphorus was found to increase in the L-F-H horizons and the surface two centimeters of mineral soil by Smith (89). The concentrations in these horizons then returned to pre-burn levels within 15 months. In the deeper mineral horizons, phosphorus levels were near or below pre-burn levels at the end of the experiment. Scholl found much higher phosphorus concentrations in the O horizon, though no change could be detected in the mineral horizons (82). Ahlgren and Ahlgren (10) and Wells et al. (99) report that slight increases in phosphorus levels in the upper mineral soil are often reported.

Smith found water-soluble forms of sodium to increase slightly immediately after burning in the L-F-H horizons, after which the sodium concentrations in all horizons decreased and remained below pre-burn levels through the end of the experiment (89). Smith attributed this to the preferential adsorption of calcium and potassium on exchange sites formerly occupied by sodium.

Acid-extractable forms of iron and aluminum were found to increase immediately after burning, while exchangeable hydrogen sharply decreased. The exchangeable cation concentrations returned to pre-burn levels, while hydrogen was decreased through the end of the experiment. In the top two cm of mineral soil, exchangeable cations sharply increased and then decreased greatly between 13 and 15 months. Exchangeable hydrogen decreased and then increased during the same period. The cations slowly leached downward, pushing high exchangeable hydrogen concentrations just below them. Fifteen months after burning, both exchangeable cations and exchangeable hydrogen were near pre-burn levels throughout the mineral soil (89).

Large losses in total nitrogen are often reported due to burning (10, 44, 99). However, in many cases nitrogen concentrations of the mineral soil are actually increased (10, 99). This can perhaps be explained by the rapid mineralization of partially decomposed organic compounds (10, 99). Nitrogen concentrations may also be increased because of the much more rapid nitrification taking place due to the increased pH commonly found in a post-fire situation. Ammonification and denitrification are also often increased by burning (10). These changes in the nitrogen cycle may last several years, although this varies (10). Biological nitrogen fixation may also be responsible for large inputs of this nutrient after fire (10, 99), as may atmospheric inputs (4).

METHODS AND MATERIALS

Two related survey studies were done. One involved the examination of 12 areas regenerated by planting. The second concerned 24 locations on which natural regeneration methods were used or had occurred naturally. These 24 locations included 12 fires (prescribed and wild) and 12 partial silvicultural harvests (shelterwood, seed tree, and strip cuts). These silvicultural situations will be called plantations, fire areas, and partial cut areas throughout the rest of this study.

In each study, locations for installation of temporary field plots were randomly selected from lists of potential study areas. These lists of potential study areas, to be called locations throughout the remainder of this study, were obtained by interviewing area foresters and visiting the sites to determine whether they met the selection criteria. It was decided that the study would be limited to the following counties: Crawford, Kalkaska, Montmorency, Ogemaw, Oscoda, Otsego, and Roscommon.

Plot-Selection Criteria

The plantations were randomly selected to meet the following criteria:

1. Greater than 3 and less than 15 years since planting

2. Large enough to contain a 20.12 m by 20.12 m (one chain by one chain) plot

3. Having a soil type matching the needs of the experimental design. The experimental design called for three plantations on coarser-textured soils, three on medium-textured soils, three on finer-textured soils or soils with fine-textured bands, and three on soils with relatively shallow water tables. These were restricted to sands or loamy sands in or near the range of characteristics described as the Grayling soil series. The locations sampled are listed in Table 2 and plotted on a map in Figure 1.

The fire and partial cut locations were selected to meet the following criteria:

1. Greater than 3 and less than 20 years since last fire or harvest

2. Large enough to contain a 60.35 m (three chain) by 120.70 m (six chain) sample grid

3. Having had jack pine as the predominant species in the last rotation

4. The fires must have had at least a partial overstory of standing, live mature jack pine at the time of the fire

5. The partial cuts must not have burned in the last rotation

6. Both fires and partial cuts must have had a soil type matching the needs of the experimental design. The design called for four coarser-textured soils, four medium-textured soils, and four

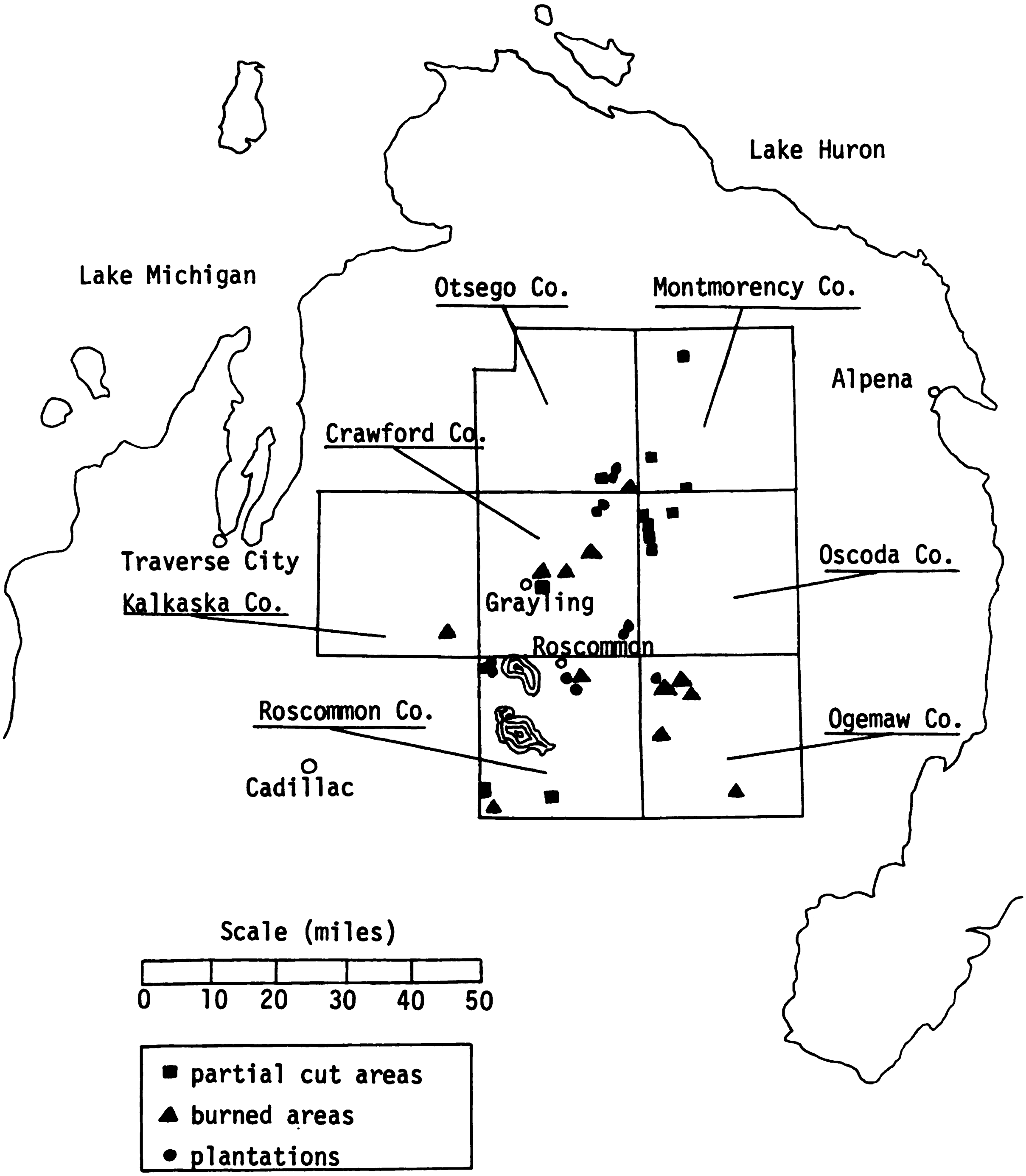

Figure 1. Locations of plantations, burned areas, and partial cut areas studied

Table 2. Legal descriptions of plantation, fire, and partial cut locations sampled in jack pine regeneration study

County	Township	Range	Section
Plantations			
Crawford	28N	1W	7
Crawford	28N	1W	7
Crawford	25N	1W	14
Crawford	25N	1W	14
Ogemaw	24N	1E	21
Otsego	29N	1W	16
Otsego	29N	1W	16
Roscommon	24N	4W	5
Roscommon	24N	4W	6
Roscommon	24N	2W	17
Roscommon	24N	2W	22
Roscommon	24N	4W	6
Fires			
Crawford	27N	2W	32
Crawford	27N	3W	34
Crawford	27N	2W	13
Kalkaska	25N	5W	17
Ogemaw	24N	1E	21
Ogemaw	23N	1E	33
Ogemaw	24N	2E	19
Ogemaw	21N	3E	8
Ogemaw	24N	2E	29
Otsego	29N	1W	36
Roscommon	24N	2W	17
Roscommon	21N	4W	29
Partial Cuts			
Crawford	26N	3W	10
Montmorency	29N	2E	31 & 32
Montmorency	32N	2E	22
Montmorency	29N	1E	5
Oscoda	28N	1E	13
Oscoda	27N	1E	5
Oscoda	27N	1E	8 & 9
Oscoda	28N	1E	32
Oscoda	28N	1E	27
Otsego	29N	1W	17
Roscommon	21N	3W	13
Roscommon	21N	4W	18

finer-textured soils or soils with fine-textured bands. This stratification was achieved by using locations with higher than average gravel and/or coarse sand contents as coarse-textured, those typical of Grayling medium sand as medium-textured, and those with slight banding or mottling in the lower profile as finer-textured. In many cases, the finer-textured soils would have fallen into the Graycalm soil series (Alfic Udipsamment, frigid, mixed). The locations sampled are listed in Table 2 and plotted on a map in Figure 1.

Plantation Data Collected

After a plantation area was selected and determined to meet the criteria, a square plot of approximately 0.0405 hectares was installed, measured, and described. A 20.12 m line between two planted rows was measured. Lines perpendicular to this line were run from each end such that they ended between the same two planted rows and were as close as possible to 20.12 m in length. On this approximately 0.0405 hectare block, henceforth to be called a plot, the area was calculated and living and dead trees were counted. Other data and samples collected included:

1. understory species and cover percentages, including woody sprouts
2. soil description
3. sod description
4. soil samples for each horizon to a depth of at least 30 cm
5. numbers and ages of natural jack pine regeneration

Fire and Partial Cut Data Collected

After a location was selected and determined to meet the fire or partial cut criteria, a starting point was randomly located such that the entire grid of plots would fit into the area. Eight 0.00405 hectare plots were installed; four each spaced 40.24 m apart along two transects 60.36 m apart. On strip cuts, the transects also had to cross both a cut strip and a residual strip. At each plot, the data and samples listed below were collected:

1. overstory species, basal area, and percent cover
2. understory species and percent coverages, including stump sprouts
3. stump and snag diameters at ground level or 15 cm
4. soil description
5. sod description
6. soil samples of each horizon to a depth of 30 cm
7. ages and numbers of jack pine regeneration

In some cases, obvious, easily delineated differences in regeneration success were observed on a plot. If the "different" area occupied greater than 30% of the plot, the plot was split and treated as two partial plots. All data were collected for each partial plot except that two soil pits were not dug and described. Most often, plots were split where large differences in understory vegetation and in numbers of seedlings could be seen. The numbers of seedlings on the partial plots were multipled by an expansion factor to compensate for the smaller area of these plots.

Common Data-Collection Techniques

All readily recognizable understory species were listed. In some cases closely related species were lumped into one category, as in the case of the sedges, grasses, lichens, mosses, and blueberries. Percentages were assigned to those species having greater than 5% area coverage. These cover percentages were ocular estimates of canopy cover. As such, few exceeded 70% total.

The percentage of the plot area occupied by stump sprouts was estimated for each species present. Stump sprouts included all sprouts from stumps cut or burned in the most recent harvest or fire, including those harvested in both cuts of a seed tree or shelterwood harvest.

Overstory trees as defined here are those trees, formerly belonging to the overstory, that survived the most recent cut or burn. They were identified as to species and their diameters at 1.4 m were measured to the nearest centimeter. The percentage of the plot covered by each species was ocularly estimated. An estimate of the horizontal dimensions of the crown within the plot was divided by the total plot area to obtain a cover percentage.

Stumps and snags from the most recent fire or harvest were counted and their diameters measured at 15 cm above the ground. Where the second shelterwood cut had already taken place, the stumps from both cuts were counted. The stumps in some of the fires were too badly burned to allow good estimates of diameter.

A soil pit was dug and described at or near the center of each plot. For each horizon, depths were measured, textures determined, and gravel and cobble percentages by volume were estimated. Any change in texture or in gravel or cobble content within the surface 150 cm of mineral soil was described. Depths to mottles were also recorded.

A sod description was also done at the soil pit on each subplot. This description involved an estimate of the thickness, and classification of the relative numbers of roots and density of the sod mat in each of the surface organic and mineral horizons. Sod density as used here refers to the rooting intensity and to the cohesiveness of the sod mat.

All living and dead jack pine trees were counted on the plantations. On the fire and partial cut plots all regeneration was counted and cut at the soil surface. The age of each tree was determined in the field if possible. If not, the bottom of the stem was brought into the laboratory, stained with dilute methylene blue, if necessary, and aged using a stereoscope. On those plots where seedling numbers were excessive, a quarter-circle was chosen at random, the trees in this quarter-circle counted and aged, and the numbers of trees multiplied by four to represent the entire plot.

Slope, slope position, and aspect were measured for each plot.

Soil samples were taken from each mineral horizon occurring in the upper 30 cm of mineral soil. Samples were taken from top to bottom of each horizon, even if the bottom of the deepest horizon extended beyond 30 cm from the surface.

Laboratory Analyses

Soil samples were air-dried as soon as possible after collection. Prior to analysis the aggregates were crushed and the samples passed through a 2 mm sieve. Organic material larger than 2 mm was disposed of. Gravel contents were determined for all sampled horizons by weighing the sieved soil samples and the gravel retained in the sieve.

Soil pH was measured on soil samples from the three upper mineral horizons using a glass electrode pH meter in a soil solution with a soil:water ratio of 1:2.

Cations were extracted from the two uppermost mineral horizons at each plot using a method similar to that described by Isaac and Kerber (53), except 200 ml of 1 N NH_4OAc was used and samples were shaken for 30 minutes in the extracting solution and did not stand overnight. Calcium, magnesium, potassium, and sodium concentrations were then determined using a Spectrametrics SMI III plasma emission spectrometer.

The method used in the particle-size analysis was similar to the pipette method described by Day (43). Some modifications were necessary because of the low silt and clay contents of these soils. Soil samples of 100 grams were used rather than 10 grams. The soil samples were dispersed in 20 ml of calgon solution instead of 10 ml. In the dry sieving process, sieves were shaken for 10 minutes rather than three. Dispersion was done in a mixer run at low speed for five minutes in samples which had been allowed to stand for 30 minutes in calgon solution. Silt plus clay contents were calculated by subtraction of the oven dry weight of the sieved sand from the oven dry weight of the total sample. Particle size analysis was performed for one plot at each location in the natural regeneration study, and for all plots in the plantation study.

Hydrogen peroxide digestion of organic matter was performed only on the A1&A2 and A1 horizons prior to particle size analysis. Rather than using a filter candle to remove the excess hydrogen peroxide solution after digestion, the samples were allowed to settle, and the supernatant was removed when it became clear. Next, a 1:4 mixture of distilled water and methyl alcohol was added to the sample. Again, when the supernatant cleared, it was removed by suction. The sample was then oven-dried.

A porous plate apparatus was used to determine moisture contents at 0.1 and at 15 bars of pressure for the three surface mineral horizons on one plot from each location in the natural regeneration study and for the three surface mineral horizons from each plot in the plantation study. Samples were allowed to soak overnight and brought to equilibrium on a 15 bar plate.

Loss on ignition was determined with a muffle furnace set at 600°C for four hours.

Total nitrogen and total phosphorus contents of the two uppermost mineral horizons were determined simultaneously on a 0.75 gram sample. This sample was digested using one Kjeltab (containing 7.5 mg Selenium and 1.5 grams K_2SO_4) and 10 ml concentrated H_2SO_4 at 420°C until digestion was complete. Digests were then cooled and diluted. This digestion procedure is similar to that of Isaac and

Johnson (52). The nitrogen and phosphorus contents were then determined colorimetrically on a Technicon AutoAnalyzer II using an ammonia-salicylate complex for the nitrogen and a phosphomolybdenum complex for the phosphorus.

Data Analyses

The results of this study were analyzed on the CDC 6500 computer at Michigan State University. Regressions, correlations, and analyses of variance were performed using the SPSS: Statistical Package for the Social Sciences (70).

Much of the data was transformed prior to analysis to force data variability into more nearly normal distributions (93). The square root transformation was used in calculating the square roots of the numbers of trees. This transformation was also used on many variables that did not include values of zero. The square root of the data value plus 0.5 was used as the transformation for all variables for which zero was a possible value (93).

Description of Study Locations

This study was restricted to the outwash plains of the Grayling-Roscommon area of northern lower Michigan. A map of the study area with the distribution of the Grayling-Rubicon-Roselawn soil association, which is found primarily on outwash plains, is shown in Figure 2 (100).

The Grayling series is very extensive in northern Wisconsin and in the upper and northern lower peninsulas of Michigan. It is, as Eyre (48) says, "typical of the poorer sandy soils." It is most

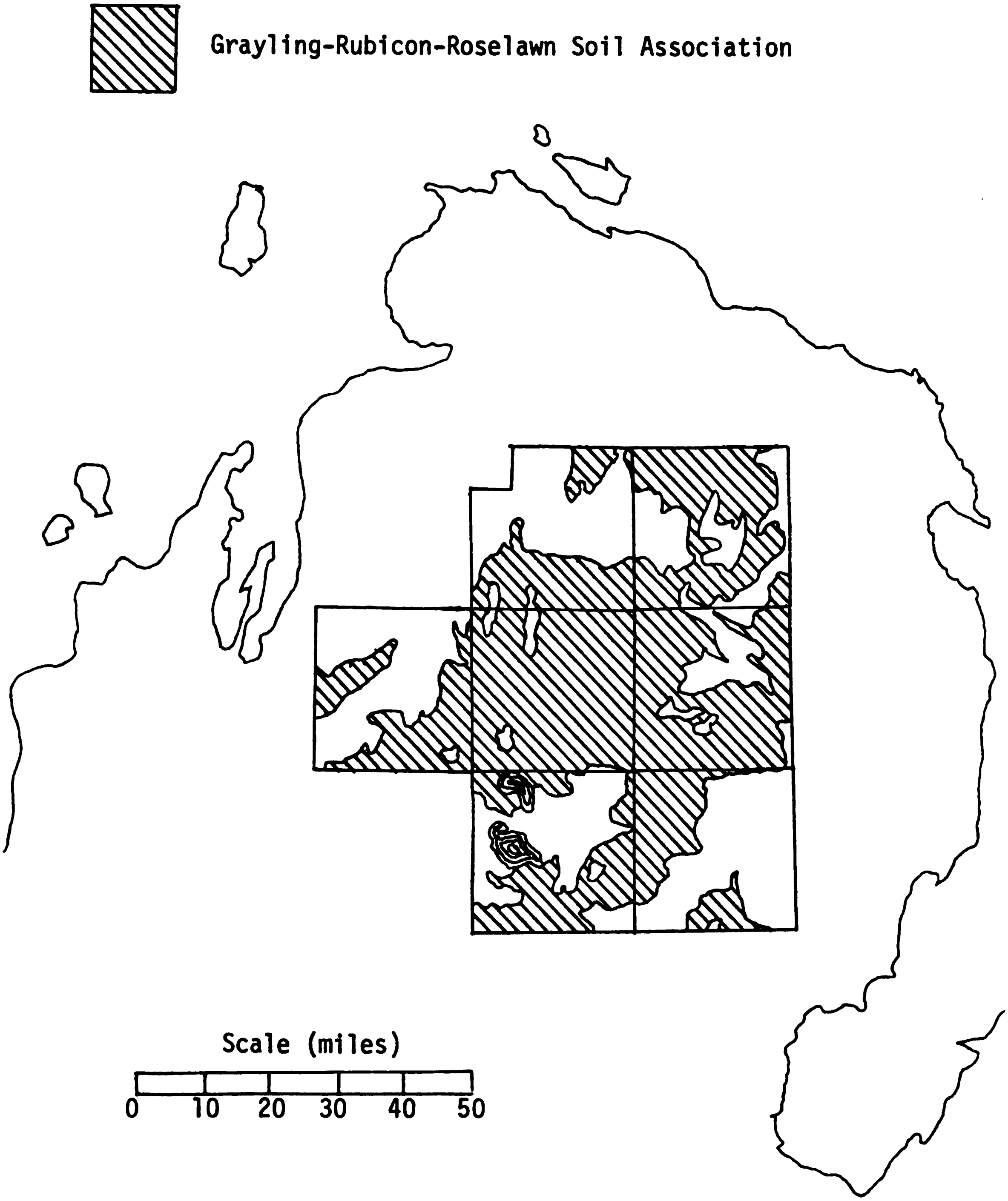

Figure 2. Extent of Grayling-Rubicon-Roselawn soil association in study area (100)

often found on outwash plains and lake plains, popularly known as jack pine plains or barrens.

This soil principally supports jack pine in the upper peninsula and jack pine and scrub oak in the northern lower peninsula of Michigan. Ground vegetation is dominated by lichens, mosses, wintergreen, sweet-fern, blueberries, bearberry, bracken fern, "dry land sedge," and sand cherry (1, 82). Soil Conservation Service (90) estimates of site index range from 12.5 to 15.2 m (41 to 50 feet) and average annual growth per acre is approximately 100 to 125 board feet per acre. Shetron (84), working in the upper peninsula, estimates site indices for this series to range from 11.9 to 14.9 m (39 to 49 feet), averaging 13.4 m (44 feet). Average volume is estimated to be 118 cubic meters per hectare.

A typical Grayling profile description is as follows (90):

Horizon	Depth (cm)	Horizon Description
A1&A2	0-8	Black (N 2/) (A1), and grayish brown (10YR 5/2) sand (A2); coated and uncoated sand grains mixed throughout the horizon, giving a salt and pepper appearance; moderate organic matter content in upper part; weak medium granular structure; very friable; very strongly acid; abrupt smooth boundary. (5 to 10 cm thick)
B21ir	8-23	Dark brown (7.5YR 4/4) sand; weak coarse granular structure; very friable; strongly acid; clear smooth boundary. (10 to 20 cm thick)
B22ir	23-38	Strong brown (7.5YR 5/4) sand; single grained; loose; medium acid; clear irregular boundary. (10 to 36 cm thick)
B3	38-58	Brown (7.5YR 5/4) sand; single grained; loose; medium acid; gradual smooth boundary. (8 to 25 cm thick)
C	58-152	Light brown (7.5YR 6/4) sand; single grained; loose; medium acid.

The principal competing series are the Rubicon, Croswell, and the Graycalm. The Rubicon and Croswell can be distinguished from the Grayling by virtue of their spodic horizons. The Graycalm can be distinguished by the presence of textural bands in the lower profile. The Grayling series is classified as a mixed, frigid, Typic Udipsamment (90).

Some of the plots were selected on soils belonging to the Graycalm series. Very thin bands, usually less than 3 mm in thickness, were found deep in the profile. Technically, these soils would fall into the Graycalm series; however, it was believed that these soils were too little different from the Grayling to be excluded from the study.

The Graycalm series is found in the central and northern lower peninsula, the eastern upper peninsula of Michigan, as well as in north-central Minnesota. It is found primarily in sand on till plains, moraines, and outwash plains. The vegetation is chiefly oak and white pine in the southern range, and jack pine and scrub oak in the northern range, according to the Soil Conservation Service soil series description (91). Site index on this series was found to average 15.8 m (52 feet), while average volume is 169 cubic meters per hectare (84).

A typical profile is described below (91):

Horizon	Depth (cm)	Horizon Description
A1	0-8	Very dark grayish brown (10YR 3/2) sand; moderate medium granular structure; very friable; many fine roots; very strongly acid; clear wavy boundary. (5 to 13 cm thick)
B21ir	8-16	Dark brown (7.5YR 4/4) sand; weak fine granular structure; very friable; common fine roots; strongly acid; clear irregular boundary. (8 to 30 cm thick)

Horizon	Depth (cm)	Horizon Description (cont'd)
B22ir	15-33	Strong brown (7.5YR 5/6) sand; weak fine granular structure; very friable; few fine roots; medium acid; gradual wavy boundary. (0 to 30 cm thick)
B23ir	33-56	Yellowish brown (10YR 5/6) sand; single grained; loose; few fine roots; slightly acid; gradual wavy boundary. (0 to 64 cm thick)
A2	56-89	Light yellowish brown (10YR 5/6) sand; single grained; loose; very few fine roots; slightly acid; abrupt broken boundary. (0 to 64 cm thick)
A&B	89-152	Light yellowish brown (10YR 6/4) sand (A2); single grained; loose; lamellae and bands of brown (7.5YR 5/4) and reddish brown (5YR 5/4) loamy sand (Bt); weak medium subangular blocky structure; friable; bands are 1/4 to 2 inches in thickness with a total accumulation of 5 inches; 5 percent by volume of pebbles; slightly acid.

The principal competing series are the Mosomo, Zimmerman, Chelsea, Coloma, and Grayling series. The Mosomo and Zimmerman series contain more fine and very fine sand. Chelsea and Coloma soils are mesic. The Grayling series lack the Bt lamellae. A soil is described Graycalm if there is any banding, though the band be as little as 2 mm in thickness. The Graycalm series is a mixed, frigid Alfic Udipsamment (91).

The stratification used in plot selection in the natural regeneration study was intended to assure sampling across the range of textures found on the Grayling series. However, due to the low variability in textures that was found, this stratification was ineffective. Differences between the strata were so small as to cause differences between the strata not to be statistically significant. Textural differences on these sites are not likely to be a factor in regeneration success. However, there were significant differences among the strata used in the plantation study (Table 10). This stratification involved a wider range of soils than that in the natural regeneration study.

RESULTS AND DISCUSSION

This section contains the results of the statistical analyses. The factors controlling regeneration and the germination patterns on the burned and partial cut areas are identified and discussed. The results of the plantation study are also presented and explained.

Site Factors Controlling Regeneration Success on Partial Cut Areas

The partial cut essentially opens up small areas within a stand, allowing new vegetation to utilize the site resources formerly allocated to the harvested trees. Usually, a large proportion of the seed reaching these sites is dispersed from the residual overstory. After these sites are reoccupied, the residual overstory is removed and the rest of the stand is regenerated by seed from the slash and from the previously established regeneration. This provides for a slower, less destructive, more aesthetically pleasing regeneration phase than do most other regeneration techniques.

The regeneration results from the partial cut plots examined in this study are summarized by location in Table 3. In examining these results, one finds that the average stocking on these plots is 1346 trees/hectare (545 trees/acre). Given the "clumpy" (31) nature of this regeneration, it is obvious that, on the average, the partial cut plots are not well stocked. For the purposes of this study a stocking level of 2500 trees per hectare (1012 trees per acre) will

Table 3. Summary[a] of partial cut area seedling numbers and selected variables by location

Location	Seedling Numbers Mean (trees/ha)	Seedling Numbers Standard Error (trees/ha)	Bearberry Cover Mean (%)	Bearberry Cover Standard Error (%)	pH of B22 Mean	pH of B22 Standard Error	Sweet-fern Cover Mean (%)	Sweet-fern Cover Standard Error (%)	Comments
CRS 1	1327	294.8	4.3	0.88	4.84	0.00972	0.6	0.29	Shelterwood, no overstory
MOS 12	814	532.6	0.7	0.26	5.44	0.004	2.0	0.51	Strip cut
MOS X	988	345.9	5.6	0.78	5.13	0.0177	4.5	0.52	Seed tree cut
MOS 2	340	103.7	1.7	0.34	5.13	0.0181	1.0	0.28	Strip cut
OSS 0	1852	681.0	0.3	0.12	5.40	0.0150	10.9	0.42	Shelterwood
OSS 2	1296	587.9	0.8	0.14	5.16	0.0217	10.4	1.00	Strip cut
OSS 3	2840	536.0	2.8	0.55	4.85	0.0160	2.8	0.55	Shelterwood
OSS 4	2994	1056.3	2.2	0.53	5.19	0.0175	0.6	0.14	Seed tree, no overstory
OSS 5	741	180.7	1.0	0.28	5.25	0.0169	1.2	0.27	Shelterwood, no overstory
OTS 2	1235	500.6	0.4	0.14	4.93	0.0175	3.1	0.46	Shelterwood
ROS X	802	308.6	2.5	0.92	5.09	0.0892	0.4	0.14	Shelterwood
ROS 3	926	258.8	0.6	0.29	5.04	0.0165	0.3	0.12	Shelterwood
Average	1346	238.0	1.91	0.48	5.21	0.190	3.2	1.08	

[a]Location means based on approximately eight plots per location, with adjustments due to missing data and partial plots.

be considered a regeneration success. Although this stocking level may seem high relative to those tolerated in plantations, these naturally regenerated seedlings are not optimally spaced and are therefore (1) likely to be of poor form and (2) likely not to fully occupy the site except at somewhat higher stocking levels. Given this criterion, only two of the locations studied would qualify as successes, and over half the locations are far below the minimum acceptable stocking.

As Caveney (31) pointed out, regeneration success is related to type of competing understory vegetation. He found that percentages of mil-acre plots stocked with jack pine were well above the study average if lichen, moss, litter, or bearberry was the dominant understory plant on a plot. He found that plots dominated by blueberry tended to be well below average stocking. Ahlgren (5) reports that such plants as bracken fern, blue joint grass, sedge, and fireweed were especially harmful to the growth and survival of reproducing jack pine seedlings.

Significant positive correlations between numbers of trees and lichen, sweet-fern, and bearberry coverage were found in this study (Table 4). Also, multiple regression equations derived from these data and summarized in Table 5 included bearberry coverage and sweet-fern coverage as significant independent variables, both with positive coefficients. These relationships can also be seen in the data presented in Table 3.

Caveney (31) attributed the higher regeneration success on lichen and moss-dominated plots to the superficial root systems of these species. The jack pine seedling has an excellent chance of surviving on these plots because its taproot is able to penetrate the zone in which the lichen or moss is competing for water.

Table 4. Significant correlations between site factors and regeneration success

Independent Variable	Correlation Coefficients	
	Trees/ha	Square Root of Trees/ha
Overstory basal area (m^2/ha)	-0.22*	-0.24*
Lichen cover (%)	0.20*	0.21*
Sweet-fern cover (%)	0.27*	0.28*
Bearberry cover (%)	0.28*	0.28*
pH of B22 horizon	-0.36*	-0.25*

*Significant at .05 level.

The reasons for the improvement in regeneration success as bearberry and sweet-fern cover increase are more speculative. It may be that these plants, with their woody root systems, do not fully occupy the surface soil, allowing the young jack pine seedlings to root alongside them. It may also be that these species have site requirements similar to those of jack pine. Their presence on a plot may indicate that unoccupied microsites suitable for jack pine seedlings are or recently were available.

Overstory basal area also had a significant effect on regeneration success, appearing in the square root of number of trees regression

Table 5. Multiple regression equations developed for partial cut plots

Equation 1.

$$\text{trees/ha} = 6800^{**} + 417\sqrt{x_1^{**} + 0.5} - 2514\sqrt{x_2^{**} + 0.5} + 477\sqrt{x_3^{**} + 0.5}$$

$$- 86(x_4^{*})$$

where x_1 = percent bearberry cover

x_2 = pH of B22 horizon

x_3 = percent sweet-fern cover

x_4 = ppm total phosphorus of B21 horizon

n = 88

R = 0.59**

SE_y = 158

Equation 2.

$$\sqrt{\text{trees/ha}} = 1272^{**} + 74\sqrt{x_1^{*} + 0.5} + 114\sqrt{x_2^{**} + 0.5} - 16.5\sqrt{x_3^{**} + 0.5}$$

$$- 481 \quad x_4^{**} + 0.5 - 99(x_5^{**}) + 114(x_6^{*})$$

where x_1 = percent bearberry cover

x_2 = percent sweet-fern cover

$x_3 = \dfrac{\text{overstory basal area } (m^2/ha)}{0.1593}$

x_4 = pH of B22

x_5 = ppm exchangeable calcium of B21

x_6 = A1&A2 thickness (cm)

n = 88

R = 0.62**

SE_y = 27.4

---

*Significant at .05 level.

**Significant at .01 level.

(Table 5). Overstory basal area increases tend to decrease numbers of seedlings, as Caveney (31) found. As the residual overstory becomes more dense, a smaller proportion of the area is unoccupied, and therefore able to support regenerating seedlings. These results should be used carefully, however, because they do not necessarily mean that heavier first cuts allow greater regeneration success. Rather, they are probably a result of sampling partial cuts on which the residual overstory had been removed as well as some on which it had not.

No differences in organic matter content or water-holding capacity in the upper mineral horizons were found between the fire areas and the partial cut areas in the natural rengeration study (Table 6). However, significant differences in profile depth, depth to mottling, and B22ir gravel contents were found (Table 6). It is likely that these differences were caused by local differences emphasized by heavier sampling for each treatment in the districts in which one treatment or the other was in favor. This may have caused some bias in the sampling, and must be considered in the interpretation of the results.

Differences in soil fertility between burned and partial cut plots were also found (Table 6). Though the differences in the treatment averages are in some cases not great, it is the great variability around these means that provided the variability upon which the regressions were based. Nitrogen concentrations in the A1&A2 horizon were significantly higher on fire areas. This will be discussed in the next section. Available magnesium and potassium concentrations were significantly higher in the B21ir horizon on the partial cut plots.

Table 6. Significant differences between partial cut plots and burned plots

Variable	Fire		Partial Cut		Probability Level
	Mean	Standard Error	Mean	Standard Error	
A1&A2 total nitrogen (ppm)	760	27.7	671	70.8	0.012
B21 exchangeable magnesium (ppm)	5.09	0.499	7.90	0.811	0.004
B21 exchangeable potassium (ppm)	2.68	0.126	3.39	0.180	0.002
B22 gravel content (% by weight)	2.34	0.0819	3.78	0.133	0.016
Overstory cover (%)	1.28	0.135	4.39	0.222	0.001
Overstory basal area (m^2/ha)	0.205	0.0215	0.699	0.0353	0.001
Sedge cover (%)	17.6	0.178	13.4	0.164	0.032
Lichen cover (%)	0.373	0.0785	1.23	0.134	0.002
Litter depth (cm)	0.851	0.0536	2.69	0.0452	<0.001
Profile depth (cm)	48.1	1.62	43.7	0.505	0.009
Depth to mottling (cm)	111	3.48	100	2.90	0.020
Regeneration (trees/ha)	7018	460	1303	64.1	<0.001

Perhaps these cations increase through a rotation and are subsequently leached when or if a stand is burned. Partial cuts are not as greatly disturbed at the end of a rotation and so the cations are not leached. Though these post-burn cation losses are not reported by Smith (89) or Scholl (82) for outwash plain soils, it may simply be that Smith and Scholl both missed them because they did not sample beyond 15 and 17 months after burning, respectively. The burned plots sampled in this study were sampled between 2 and 19 years, with an average of 7 years after burning. However, these higher cation concentrations may be associated with the sampling bias discussed above.

These higher cation concentrations are associated with decreased numbers of seedlings as indicated by the negative correlation between pH of the B22ir horizon and numbers of trees (Tables 3 and 4). The negative effect of fertility is also demonstrated by the negative coefficients of the pH of the B22ir horizon and of the total phosphorus and exchangeable calcium contents of the B21ir in the regression equations (Table 5). Also, an analysis of variance on plots broken down by regeneration success found that those plots with greater numbers of trees had significantly lower pH's in all three surface mineral horizons.

This negative effect of fertility can be understood if one considers the ecological niche of jack pine. It is able to survive at lower nutrient status than any other commonly planted Lake States conifer (102). It is likely that it is most competitive on low-fertility sites because of the absence of other, more demanding species.

Partial Cut Regeneration Patterns

The regeneration patterns for the partial cut areas are plotted in Figures 3 and 4. Some partial cuts begin to regenerate the year following the first cutting, while on others, there is a one- to two-year lag. In nearly all cases there are six to seven years of relatively good regeneration followed by a gradual decrease. Seedlings may continue to germinate as long as 11 years after cutting. The reasons for the timing of this process might include differences in yearly seed crops, weather conditions, competition, and seedbed conditions. It was attempted to relate partial cut year-to-year regeneration success to weather information from U.S. Weather Bureau stations in the area, but no strong relationships were found. The complexity of the response of seeds and seedlings to weather conditions and the large variation in precipitation over short distances make this relationship difficult to define.

Site Factors Controlling Regeneration Success on Burns

Although jack pine is naturally adapted to post-fire regeneration, burning does not necessarily guarantee successful regeneration. First, there must be an adequate seed supply. Second, given an adequate seed supply, site conditions must be such that jack pine is able to germinate and third, the seedling must be competitive enough to survive.

Burning greatly alters the condition of the site. Usually, the overstory is killed. Understory plants may also be killed or severely damaged, depending on their adaptations to burning and on the

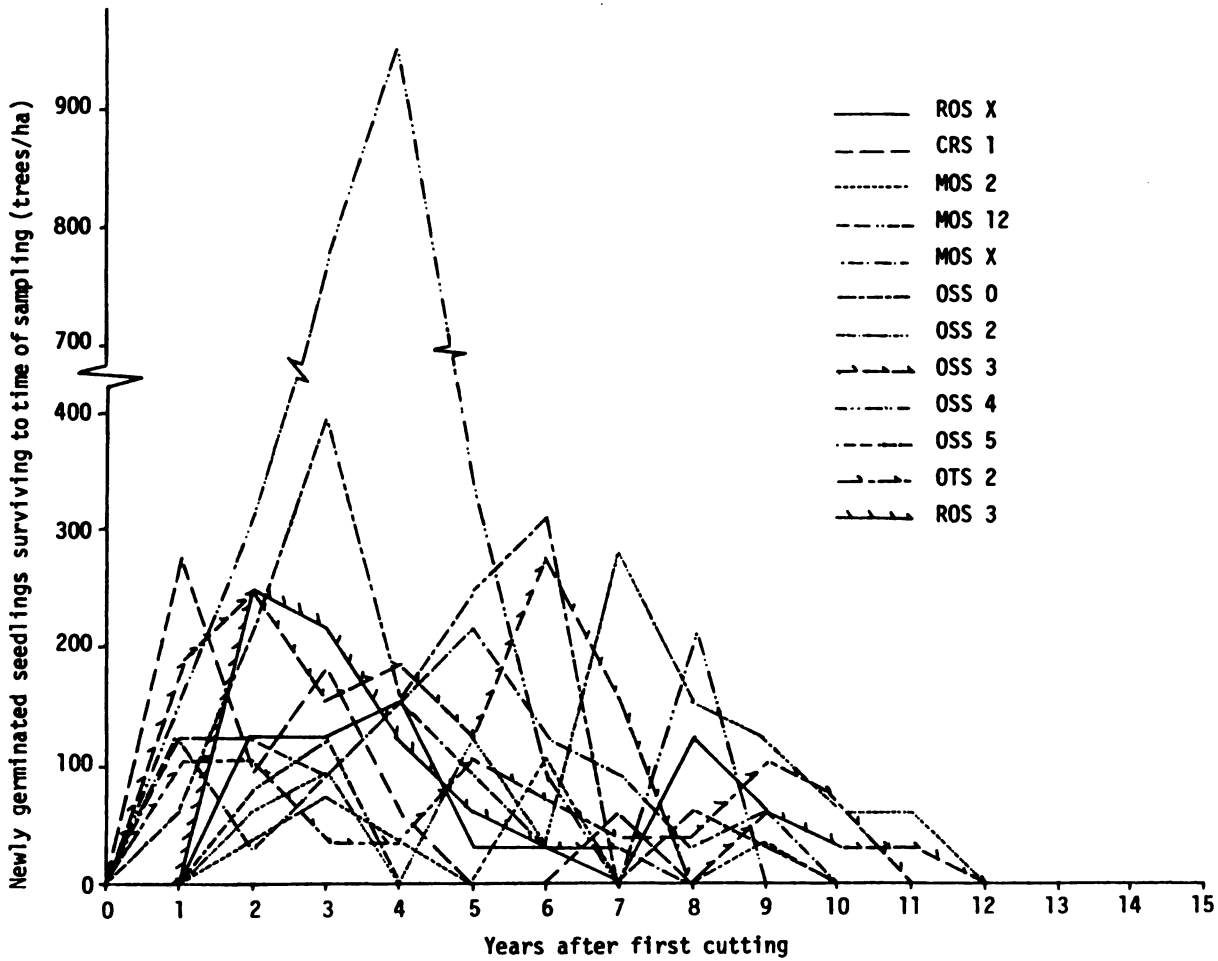

Figure 3. Age distributions of surviving seedlings on partial cut areas

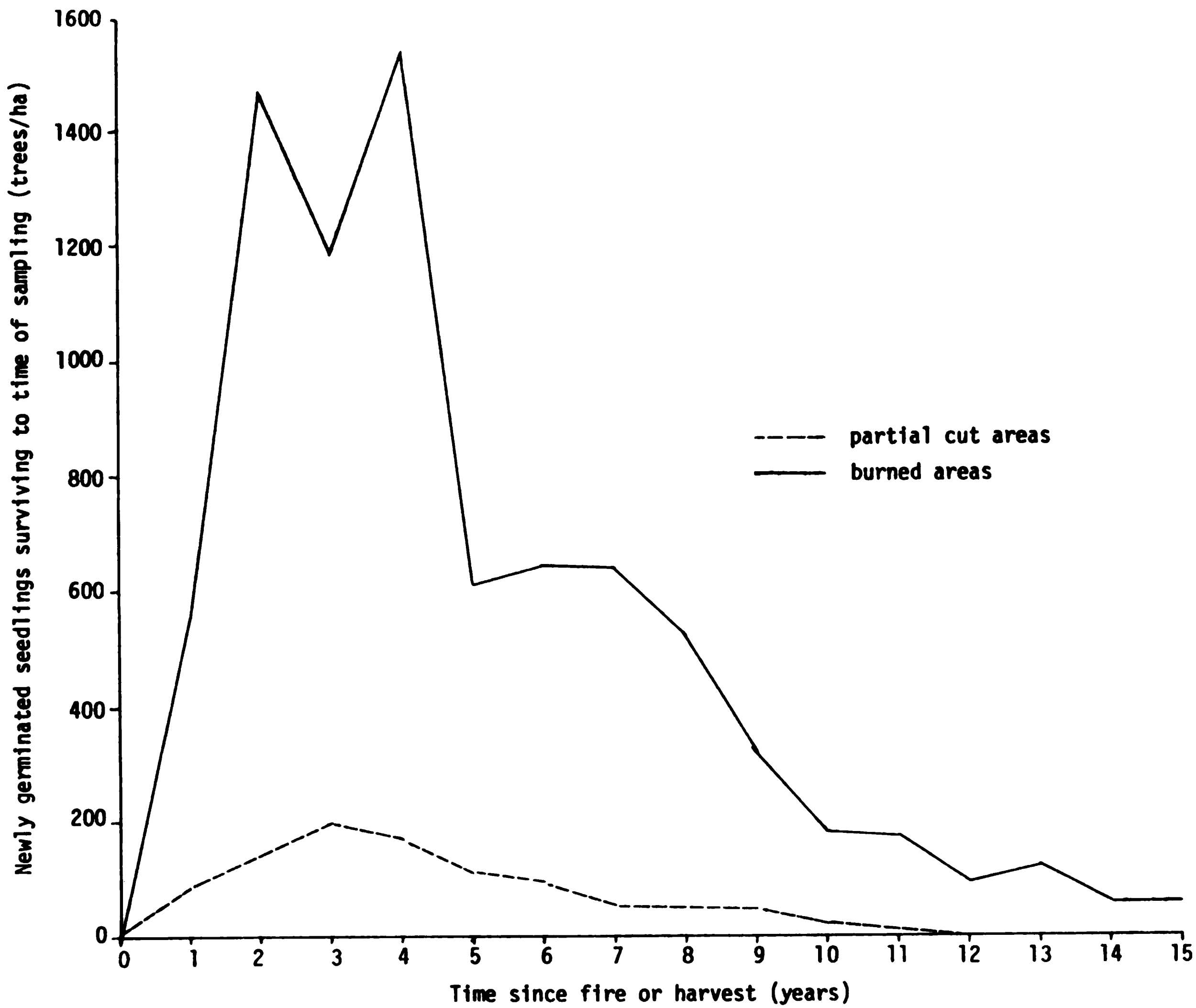

Figure 4. Average age distributions of surviving seedlings on burned areas and partial cut areas

severity and type of fire. Lichen coverage, for example, is often greatly reduced by burning, while sedge coverage is usually increased (Table 6).

This rapid mortality leaves the site largely unoccupied. However, burning often kills only the aboveground portions of a plant. As Darlington (42) pointed out, the great majority of the plants on the outwash plains have some type of deep roots or rootstocks able to survive a fire and reproduce vegetatively afterward. Ahlgren (10) discussed the abilities of blueberry and bracken fern to do this.

Besides killing or damaging the vegetation, the fire also consumes a large proportion of the forest floor. This study found the depth of the forest floor to be significantly reduced on the burned areas relative to the partial cut areas (Table 6). This in itself is an important effect, as a large body of Canadian literature has shown that the reduction of the forest floor improves germination and survival. According to Chrosciewicz's classification (39), the average burned plot in this study was a high-quality seedbed, while the average partial cut plot was of only moderate quality. The differences in regeneration success between the two treatments are probably partially due to differences in litter depth, although it was not a significant variable in any of the regressions or correlations with numbers of trees. This, however, is probably due to the analysis of the two data sets separately.

A secondary effect of the reduction in litter depth is the subsequent release of large amounts of nitrogen into the mineral soil. Partial combustion changes many of the organic nitrogen-containing compounds in the remaining litter into easily mineralized forms (10, 99). This process manifested itself in this study as a significantly higher total nitrogen content in the A1&A2 horizon on the burned plots (Table 6).

Significantly more seedlings were found on the burned plots than on the partial cut plots. This can be seen in Table 7, where 7 of the 12 locations were "successes," as measured by the criterion of 2500 trees/ha established earlier. Of those locations not meeting the criterion, only two are far below it. The average stocking of 7123 seedlings/ha on the burned plots is well above the minimum considered a success. These results are in sharp contrast to the partial cut stocking levels.

As was mentioned earlier, sedge cover was found to be significantly higher on the burned than on the partial cut areas (Table 6). Sedge cover is also more strongly correlated with numbers of trees than any other variable and it has a negative correlation (Table 8). It is also a significant variable in the multiple regression equations, with negative coefficients (Table 9). In short, more sedge means less trees, and this factor may have greater control over tree numbers than any other factor measured.

The negative effect of the sedge cover can be seen in Table 7. The location with the highest average stocking is the lowest in sedge cover. In contrast, the location with the lowest stocking has the greatest sedge cover. This relationship can generally be seen at the other locations also, although averaging all of the plots at a location and compensation by other factors in some cases weakens it.

Table 7. Summary[a] of fire area seedling numbers and selected variables by location

Location	Seedling Numbers (trees/ha)		Sedge Cover (%)		B21 Thickness (cm)		Bearberry Cover (%)		Comments
	Mean	Standard Error	Mean	Standard Error	Mean	Standard Error	Mean	Standard Error	
CRF X	13300	970	28.6	0.41	11.59	0.162	0.3	0.12	Wildfire
CRF 5	11720	1320	36.8	1.04	11.94	0.135	8.8	0.95	Wildfire
CRF 6	2960	406	33.8	0.62	8.89	0.339	1.2	0.44	Wildfire
KAF 2	4930	528	13.3	0.78	9.45	0.103	0.0	0.0	Wildfire
OGF 2	13020	1650	36.5	0.45	7.62	0.257	0.0	0.0	Wildfire
OGF 5	24200	3060	3.2	0.58	8.41	0.180	3.0	0.63	Wildfire
OGF 7	2110	255	42.7	0.84	8.76	0.163	0.6	0.24	Prescribed burn under seed trees
OGF 8	8020	2120	20.0	0.32	8.57	0.171	0.4	0.14	Wildfire
OGF *	741	108	23.3	0.73	7.26	0.104	1.5	0.56	Light wildfire Live overstory
OTF 1	2190	233	9.6	0.79	8.57	0.108	0.6	0.14	Wildfire
ROF 5	309	55.9	44.8	0.38	8.89	0.129	0.8	0.14	Prescribed burn
ROF 9	1980	257	36.9	0.35	7.78	0.141	0.1	0.09	Wildfire
Average	7123	2081	27.5	3.91	8.98	1.44	1.4	0.71	

[a]Location means based on approximately eight plots per location, with adjustments due to missing data and partial plots.

Table 8. Significant correlations between site factors and regeneration success on burned plots

Independent Variable	Correlation Coefficients	
	Trees/ha	Square Root of Trees/ha
Sedge cover (%)	-0.37*	-0.37*
B21 thickness (cm)	0.21*	0.22*
Sweet-fern cover (%)	0.18	0.24*
Bearberry cover (%)	0.18	0.20*
Depth to mottling (cm)	-0.16	-0.26*

*Significant at .05 level.

It is easy to see why sedge is so important. Like jack pine, it is well-suited to regenerating under post-fire conditions. Although sedge is often found in older stands, it is less common as stands grow denser, as indicated by its significant negative correlations with overstory cover and overstory basal area on the partial cuts. Ahlgren (9) discusses its low frequency in mature red and white pine stands. Nonetheless, Ahlgren found live seed in the forest floors of these stands. He also found high sedge frequencies and seed numbers in recently prescribed-burned jack pine stands in northeastern Minnesota. Personal observation suggests that this species may also reproduce vegetatively after light to moderately severe fires.

Sedge is an extremely competitive species under post-fire conditions. It forms a dense root mat in the A1&A2 and upper B21ir horizons. Field sod descriptions indicated that this mat was usually much

Table 9. Multiple regression equations developed for burned plots

Equation 3.

$$\text{trees/ha} = -2518\sqrt{x_1^{**} + 0.5} + 7824\sqrt{x_2^{**} + 0.5} + 2077\sqrt{x_3^{*} + 0.5}$$

where x_1 = sedge cover percentage

$x_2 = \dfrac{\text{thickness of B21 horizon (cm)}}{2.54}$

x_3 = bearberry cover percentage

$n = 92$

$R = 0.67^{**}$

$SE_y = 1017$

Equation 4.

$$\sqrt{\text{trees/ha}} = 1437^{**} - 242\sqrt{x_1^{**} + 0.5} + 125(x_2^{**}) + 296\sqrt{x_3^{**} + 0.5} - 51.3(x_4^{**}) + 1.85\sqrt{x_5^{*} + 0.5}$$

where x_1 = sedge cover percentage

x_2 = profile depth (cm)

x_3 = bearberry cover percentage

x_4 = depth to mottling (cm)

$x_5 = \dfrac{\text{total basal area } (m^2/\text{ha})}{0.1593}$

$n = 88$

$R = 0.66^{**}$

$SE_y = 72.0$

*Significant at .05 level.

**Significant at .01 level.

thicker on recent burns than on partial cut areas. The importance of this sod is magnified by the low water-holding capacity of these soils. Soil moisture depletion is never more than a few days away, and the jack pine seedling must get a taproot beneath this sod mat and into a more stable, less competed-for water source. The deeper this sedge root mat is, the lower is the probability that the seedling will survive long enough to sink a taproot through it. It may be that the jack pine seedling's chances of survival are further reduced by an allelopathic effect of the sedge.

In many cases during the field data collection, plots were split where one section of the plot was dominated by sedge and another by other understory species, with in almost all cases far fewer surviving jack pine in the portion of the plot dominated by the sedge. The sedge is excluded from certain areas in stands in which it is otherwise the dominant understory plant. The reason for the exclusion in these areas may be that a denser overstory decreased the amount of sedge in the understory prior to the burn, thereby decreasing sedge seed supplies and increasing the competitiveness of other species. It may also be due to more intense burning around the deeper litter layers and heavier slash accumulations occurring where the stands are denser. There, hotter fires might kill more of both the seed in the forest floor and the sprouting underground portions of the plant.

Sedge cover was found to have had a correlation of -0.55 with years since burning. This may be due to the fact that on some of the older burned plots the regeneration had closed crowns, thereby beginning to exclude sedge from the understory.

Bearberry cover was found to be significantly and positively correlated to regeneration success (Table 8). It was also a significant variable in the regression equations (Table 9). Again, the positive effect of the presence of this species may be due to its less competitive relationship with jack pine seedlings, or may be due to its tendency to grow under conditions similar to those favoring jack pine.

Two interesting and apparently very important variables in the regression equations are profile depth and thickness of the B21ir horizon (Table 9). It is relatively easy to understand the importance of the thickness of the B21ir, since this horizon is probably the site of a large portion of the jack pine root systems. The thicker this horizon is, the more site resources are available to the jack pine seedling. The resources in this deeper horizon are by and large not available to the shallower-rooted herbaceous competition. The most important of the resources being discussed here is probably water, since higher fertility would favor other woody species and would put the jack pine at a competitive disadvantage. The total profile depth is probably important for similar reasons. Profile depth is significantly related to depth of the B21ir and is probably roughly equivalent to rooting depth. Again, deeper profiles provide more site resources to the trees, but are of less value to the competing herbs. It is also possible that the deeper profiles are able to support a denser overstory, shading out the sedge and yielding more slash and litter. Thus, the effects of the deeper profiles would favor the seedling indirectly.

Depth to mottling is significant in the regression and simple correlation of square root of tree numbers (Tables 8 and 9). The coefficients are negative, meaning that deeper mottles tend to result in fewer trees. Where mottles are quite shallow, they indicate the presence of standing water during some part of the year within reach of the seedling root systems. Where mottles are deeper, they are not likely to affect the seedlings themselves; however, their presence may have an indirect effect by supporting a denser parent stand.

Total basal area of the pre-fire stand is also a significant variable in the square root regressions (Table 9). Its effect is positive. Total basal area is a variable combining the basal area of the live overstory with stump cross-sectional areas and the cross-sectional areas of snags at stump level (15 cm). This variable is thus a rough measure of the density of the pre-fire stand. Its importance, discussed above, is that heavier pre-fire stocking results in a less vigorous understory and in some cases in more intense fires due to heavier slash loading and deeper litter layers. Also, more seed may be available.

The correlation coefficients obtained for the multiple regression equations developed in this natural regeneration study are rather low, although not unusually so for this type of study. This means that a fairly large proportion of the variability in stocking cannot be explained by the factors measured. Large differences in seed availability were no doubt partially responsible for this unexplained variation. Also, the effects of weather were not accounted for by variables in the equation. Mortality caused by insects, rodents, and other herbivores was also likely to have been a contributing factor. Perhaps the most important reason for this unexplained variability, however, is the fact that the site factors were often measured long after much of the regeneration became established, during which time site conditions are likely to have changed.

Burn Regeneration Patterns

One of the most interesting results of this study is the post-fire germination pattern of surviving jack pine seedlings. The literature on germination patterns is dominated by reports of heavy germination the year following a fire, with small numbers of germinants in the years immediately following (5, 32, 35). Beaufait (26), however, noticed a lag in germination in northern Michigan. This lag was obvious in this study also, as shown in Figures 4 and 5. In most cases, either few seedlings germinate or few survive in the first year following the fire. Maximum germination of surviving seedlings then occurs in the second, third, fourth, or fifth year after burning. Figure 4 shows that the fourth year has the highest germination, on the average. The peak at two years is entirely due to area OGF 8. Much of the seed germinating beyond the fifth year is probably from cones on the regenerating seedlings.

Beaufait (26) attributed this late germination to "apparent dormancy." Yet, high germination is often reported in other studies, often within days of dispersal. It is possible that the early-germinating seeds do not survive on these sites, due to the low osmotic potentials caused by the high cation concentrations in the post-burn

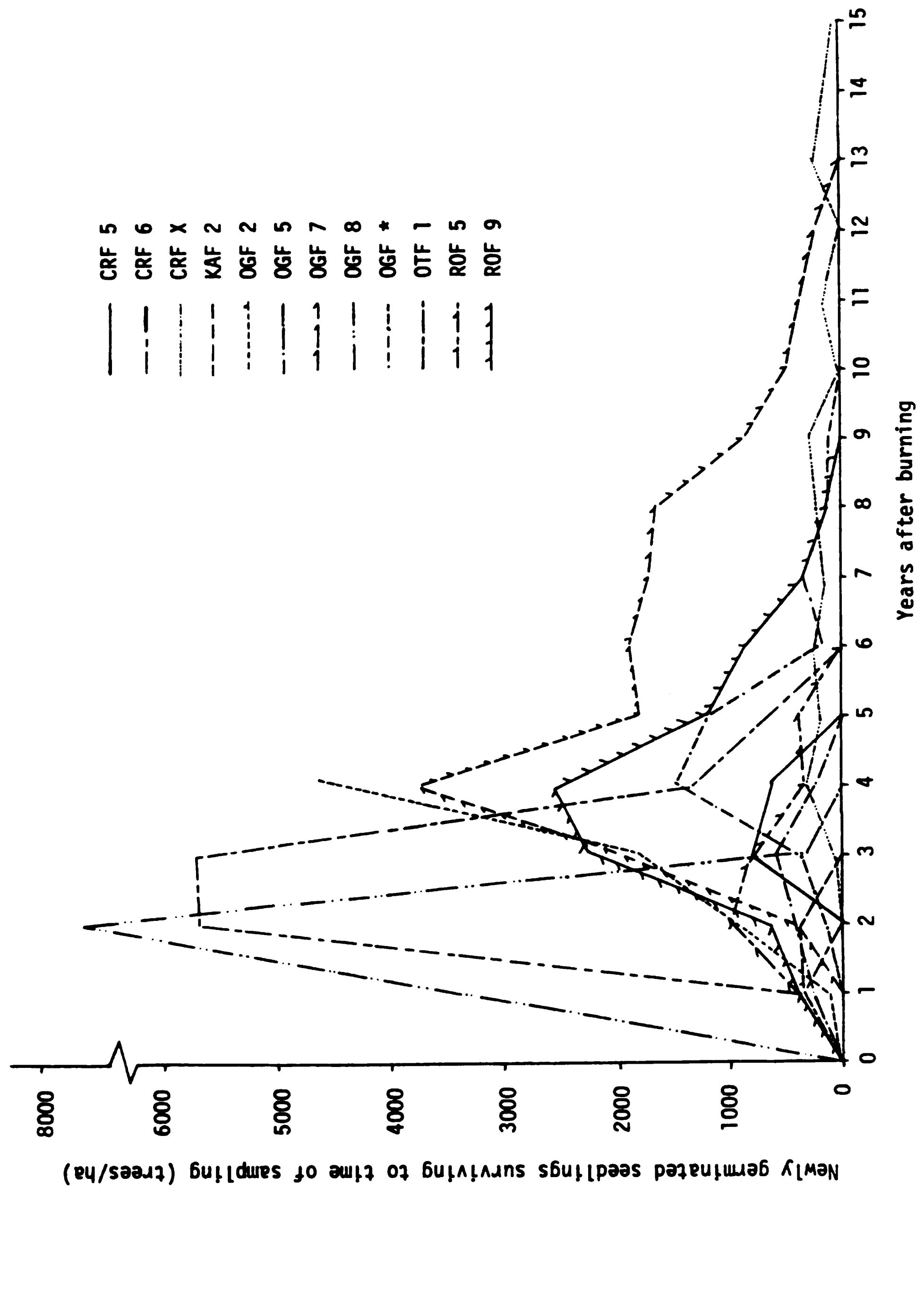

Figure 5. Age distributions of surviving seedlings on burned areas

ash (5), to the high temperatures on the blackened soil surface, or due to other causes. However, these conditions are not likely to persist for more than one or two growing seasons and thus do not explain the longer lags. Also, if germination followed by high mortality were occurring, there would be little seed left behind to germinate in subsequent years.

A better explanation might be that the conditions necessary for germination do not commonly occur until several growing seasons after burning. The characteristics of the seedbed likely change a great deal in the time immediately after the fire. The partially consumed litter is rapidly decomposed, charcoal is washed out and blown away, the released nutrients are fixed or leached downward, and a dense understory often develops. The moisture supply available to the seed might be increased enough to allow germination by any of these.

Jack pine seems to be one of the few tree species in which the seed is able to survive in the soil until conditions suitable for germination develop. Perhaps this ability to survive for long periods without germinating is related to its ability to survive for several years sealed in the cone. It may also be the result of the slower germination sometimes reported for older seed (2, 25, 35).

Germination requires some minimum number of days above a certain temperature in which plentiful water is available to the seed (19, 48). However, litter seedbeds often have poor water relations, as discussed in the Literature Review. The sandy soils beneath the forest floor on these sites are likely to worsen the problem because they are not able to replenish moisture levels as the forest floor dries. The seed might thus be stored, with its moisture absorption requirement only partially met, until the next spring, and perhaps the next, and so on. The same dry conditions delaying germination would tend to reduce damage to the seed by fungi and other seed-killing organisms.

Plantation Regeneration Success

The differences between plantation silviculture and natural regeneration are great. Yet, by knowing how jack pine responds to site factors under natural conditions, one can better understand its response to the various aspects of plantation silviculture.

The need for site preparation prior to burning on sod-dominated sites has long been known. This has most often been done using a V-blade or a disk. This treatment peels away the sod and the sod-supporting A1&A2 horizon. It ensures that the roots of the seedling are placed directly into that part of the soil in which they are most competitive, and that they are placed there essentially free of competition.

There seems to have been a rather common practice in the past of furrowing, allowing several years to pass, and then planting the furrows. Although a jack pine seedling may still survive under these conditions on dry sites because of its competitive advantage, it will grow more slowly because competition has already begun to reinvade the furrows. On somewhat better sites, these furrows revegetate more rapidly and more heavily and are likely to cause significant mortality of planted seedlings. Therefore, planting should follow furrowing within a reasonably short time.

This study examined plantations on a range of textures and on soils influenced by a water table. There were significant differences in vegetation and fertility among the different textures and drainages (Table 10); however, site preparation prior to planting apparently made these differences in site factors unimportant to the survival of planted seedlings (Table 11).

Table 10. Variables significantly different among texture and drainage strata in plantation study

Litter depth (cm)**
A1&A2 exchangeable magnesium (ppm)**
A1&A2 exchangeable calcium (ppm)***
Sedge cover (%)*

*Significant at the .10 level.

**Significant at the .05 level.

***Significant at the .01 level.

Table 11 shows the similarity in survival rates among the strata. The reasonably high survival percentages (averaging 75.4%) indicate that planting is a viable regeneration technique on all these types of sites. The table also shows the high variability in tree numbers among locations.

Planting therefore offers a simple means of reestablishing jack pine. Little attention need be given to the site factors,

Table 11. Plantation data summarized by location and by stratum

Stratum	Location	Number of Trees Mean (trees/ha)	Number of Trees Standard Error (trees/ha)	Survival Mean (%)	Survival Standard Error (%)
Coarse-textured	CRP 1	3733	--	57.6	--
	CRP 2	3246	--	82.1	--
	OTP 2	1388	--	72.2	--
	Total	2789	289.3	70.6	7.10
Medium-textured	CRP FH	2437	--	88.8	--
	CRP 5	1519	--	68.1	--
	ROP 3	978	--	79.6	--
	Total	1645	172.5	78.8	5.97
Fine-textured	CRP 2H	1439	--	65.6	--
	ROP 1	747	--	85.7	--
	ROP 4	1776	--	86.1	--
	Total	1321	122.8	79.1	6.78
Water-table-influenced	CRP FL	2014	--	82.6	--
	CRP 2L	1010	--	56.3	--
	OTP 1	771	--	80.0	--
	Total	1265	154.1	73.0	8.36
	Grand total	1755	112.03	75.4	3.228

relative to that needed in the use of the natural regeneration methods. It is more applicable to large areas for this same reason. However, planting introduces some of its own problems. Poor planting quality was found by Rudolf (77) to be the major cause of plantation failure. This is a problem because tree planters are often poorly paid and not motivated to insure the success of the operation. Poor seedling quality may be a problem also. This can usually be traced directly back to the nursery, although shipping and storage of stock may also be factors. Last, heat and drought will kill large numbers of seedlings in some plantations. This factor cannot be controlled, but its effects can be minimized by creating otherwise ideal conditions for the survival of the seedling.

SUMMARY AND RECOMMENDATIONS

The primary objective of this study was to identify the site factors exercising greatest control over jack pine regeneration success. A second objective was to develop criteria for selection of regeneration method by site types.

Temporary field plots were installed at 36 locations on sand plain sites throughout the Grayling-Roscommon area. Regeneration success was measured by counting all living and dead seedlings on the plots. The seedlings were cut and aged, except on the plantations. Vegetation and soils were described and soil samples taken. Physical and chemical properties of the soils were determined in the laboratory. Multiple regression equations were developed, analyses of variance performed, and correlations computed to determine what site factors were related to regeneration success.

Jack pine regeneration can be obtained only by meeting the requirements of a series of three steps in the process of seedling establishment. These steps are:

1. Seed dispersal--seed availability often limits regeneration success because of seed locked up in serotinous cones, because of seed mortality due to slash burning, or because of a lack of seed in the parent stand.

2. Germination--germination depends upon water availability during periods of warm temperatures. The water requirement for

germination may not be met because of a lack of water due to inadequate precipitation or because of seedbed conditions decreasing the availability of water to the seed.

3. Establishment--after germination, the seedling's taproot must quickly penetrate the litter to reach a more reliable source of moisture. However, it often encounters intense competition with understory species for the moisture in the surface soil, so the seedling must root even deeper, below the reach of the roots of the understory plants. If water becomes limiting at any time before the seedling penetrates the litter and the zone of intense competition, the seedling is not likely to survive.

Planting of seedlings is often more reliable than the natural regeneration techniques because the first two steps described above are not left to chance. This study found planting to be a viable regeneration technique on all of the site types likely to be encountered on the outwash sands of the Grayling-Roscommon area. A stratification by texture and drainage failed to find differences in stocking or in survival, although significant fertility and vegetation differences were found among the strata. Survival averaged 75.4% on the plantations sampled and average stocking was 1755 trees/ha (711 trees/acre). Stocking was highly variable, ranging from 747 trees/ha (303 trees/acre) to 3733 trees/ha (1512 trees/acre).

Stocking on the partial cut areas averaged 1346 trees/ha (545 trees/acre). A minimum acceptable stocking level of 2500 trees/ha (1012 trees/acre) was suggested. Two of the partial cut locations were able to meet this stocking requirement (Table 3). Seedling numbers were found to be positively related to percent bearberry, lichen, and sweet-fern cover, probably because the seedling is better able to compete with these species. Seedling numbers were inversely related to overstory basal area. Fertility, as measured by pH of the B22 and by total phosphorus and exchangeable calcium of the B21 horizons, was found to be inversely related to regeneration success. This negative effect may be a result of the increased ability of associated species to compete as soil fertility increases.

The partial cut areas usually begin to regenerate within one or two years after the first cutting. Seedling establishment is then relatively good for six to seven years, after which it gradually decreases. No strong relationships between weather conditions and year-to-year seedling establishment were found.

The use of partial cuts is likely to often result in failure. The reasons for the successes of two partial cut locations in this study are not clear. They are not exceptionally high or low in any of the site factors found to have significant effects on regeneration. Because successes are few and cannot be explained when they occur, the use of these regeneration techniques is not recommended. If, however, the decision is made to regenerate using partial cut methods, the highest probability of success exists on those sites with greatest bearberry, sweet-fern, and/or lichen cover. If nonserotinous cones are present, trees bearing such cones should deliberately be left in the residual overstory. If nonserotinous cones are few or not present, if sedge cover is heavy, or if a large oak component is present in the stand, partial cut techniques are likely to fail to regenerate jack pine at an acceptable level.

This study found an average of 7123 trees/ha (2885 trees/acre) on burned sites with adequate seed trees. Seven of the 12 locations examined had greater than 2500 trees/ha and may, therefore, be considered successes. Only two of the locations were far below acceptable stocking levels. This treatment is therefore more likely to be successful than the partial cut techniques.

Regeneration success on burns is inversely related to sedge cover. The sod formed by sedge is apparently very competitive with jack pine seedlings in the surface horizons, killing the seedlings before they are able to penetrate the sod. Sedge cover seems to be decreased where fires burn hotter.

Seedling numbers on burns are positively related to bearberry and sweet-fern cover, as they were on the partial cut plots. They are also positively related to basal area of the parent stand. This is attributed to hotter fires, less sedge, and possibly greater seed availability where stands are denser. A positive relationship between seedling numbers and B21 horizon thickness and/or profile depth was also found. Shallower mottles tend to increase regeneration success as well.

Seedling establishment on these burned sites was found to be at a maximum two to five years after burning. This regeneration pattern contradicts much of that found in the literature. It is likely to be caused by some change in seedbed conditions or by some physiological requirement within the seed that must be met before germination will occur.

Beaufait (26) suggests that the use of slash burning under seed trees be avoided in stands with less than 22.9 square meters of basal area per hectare or yielding less than 48 cm of evenly distributed slash. He suggests leaving 30 to 123 seed trees per hectare. However, 30 trees per hectare are not considered sufficient on these sites. The trees left in the overstory for this treatment should be the best in the stand and able to survive the shock of release, to resist windthrow, and to improve the genetic quality of the next rotation. They should also be selected based on abundance of serotinous cones. If the stand has a large proportion of nonserotinous cones, other regeneration techniques should be considered.

This treatment may be restricted by the danger of potential wildfires and by the infeasibility of burning large areas. With the lack of consolidated ownerships on much of the state land in the northern lower peninsula, escaped fires could be an especially serious problem. Also, this method is strictly limited by weather conditions since only a few days of each year are appropriate for controlled burning.

Potential exists for utilizing this method for Kirtland's Warbler management. The warbler nests in clumps of dense regeneration in areas with a fire history. Rather than managing large areas of public lands in the range of the warbler for both timber and warbler habitat, it might be more effective to manage individual areas for one use or the other. Dense regeneration could be fairly consistently obtained if small, dense, unharvested isolated stands were burned under dry conditions. The burn would have to kill the overstory, kill as much of the understory as possible, and release the seed from serotinous cones in the crowns. Although this method would cause the loss of some merchantable jack pine timber, it might provide for the needs of the warbler on smaller areas of land, allowing a timber orientation in the management of the remaining area, and overall productivities might increase.

In summary, planting can be expected to succeed on any site found on the outwash plains of this area, given adequate site preparation, good planting stock, and a careful planting job. The partial cut methods are very likely to fail on these sites. Burning without a harvest or with a partial harvest is more likely to succeed, with the probability of success increasing with greater stocking in the residual stand. This method should be restricted to well-stocked stands dominated by trees with serotinous cones.

This study has identified needs for further research in several areas. Given the strong effect of competition on survival, the use of herbicides should be considered. If the competing vegetation in the A1&A2 horizon is killed, jack pine might be able to root in this moister, more fertile horizon, and thereby survive and grow faster. If a sufficient increase in site index and stocking is obtained, it might make jack pine management a more economical operation.

The minimum number of trees to be left in stands being burned as suggested by Beaufait seems to be too low for these sites.

Research is necessary to determine the minimum number of trees to be left.

The use of the scalper-seeder for spot seeding deserves more study. This method should work with good-quality seed and appropriate seed treatment, which may be the factors limiting this technique. Again, the use of herbicides, allowing placement of the seed into the A1&A2 horizon, would improve the moisture conditions in the soil surrounding the seed, perhaps providing for more reliable germination.

There is a great need to determine the cause of the late germination observed on the burned sites in this study. If a change in seedbed conditions is occurring, knowing what that change is might make it possible to set seedbed requirements for germination. If there is some physiological reason for the delayed germination of the seed that can be overcome, it might explain the long history of seeding failures in this area and might bring cheaper methods of regeneration involving seeding back into consideration.

LITERATURE CITED

LITERATURE CITED

1. Abrams, M. D. and D. I. Dickmann. 1980. The effect of prescribed burning on plant succession on jack pine sites in northern lower Michigan. Unpub. Progress Report.

2. Ackerman, R. F. and J. L. Farrar. 1965. The effect of light and temperature on the germination of jack pine and lodgepole pine seeds. Tech. Rpt. No. 5, Faculty of Forestry, Univ. of Toronto.

3. Adams, J. L. 1966. Prescribed burning techniques for site preparation in cut-over jack pine in southeastern Manitoba. Pulp and Paper Magazine of Canada, Woodlands Review, December (1966): 574-584.

4. Adams, P. W. and J. R. Boyle. 1980. Effects of fire on soil nutrients in clearcut and whole-tree harvest sites in central Michigan. Soil Sci. Soc. Am. J. 44:847-850.

5. Ahlgren, C. E. 1959. Some effects of fire on forest reproduction in northeastern Minnesota. J. For. 57:194-200.

6. ____________. 1960. Some effects of fire on reproduction and growth of vegetation in northeastern Minnesota. Ecology 41: 431-445.

7. ____________. 1976. Regeneration of red and white pine following wildfire and logging in northeastern Minnesota. J. For. 74:135-140.

8. ____________. 1979a. Buried seed in the forest floor of the Boundary Waters Canoe Area. Minn. For. Res. Notes No. 271.

9. ____________. 1979b. Buried seed in prescribe-burned jack pine forest soils, northeastern Minnesota. Minn. For. Res. Notes No. 272.

10. Ahlgren, I. F. and C. E. Ahlgren. 1960. Ecological effects of fires. Bot. Rev. 26:483-533.

11. ______________________________. 1965. Effects of prescribed burning on soil microorganisms in a Minnesota jack pine forest. Ecology 46:304-310.

12. Alban, D. H. 1977. Influence on soil properties of prescribed burning under mature red pine. USDA For. Serv., North Cent. For. Expt. Sta., Res. Pap. NC-139.

13. Amundson, D. C. and H. E. Wright, Jr. 1979. Forest changes in Minnesota at the end of the Pleistocene. Ecol. Monographs 49:1-16.

14. Anderson, R. C., L. L. Loucks, and A. M. Swain. 1969. Herbaceous response to canopy cover, light intensity, and throughfall precipitation in coniferous forests. Ecology 50:255-263.

15. Anon. 1931. Spring fires on the jack pine plains. USDA For. Serv., Tech. Notes No. 44.

16. ____. 1937. Heat more injurious than lack of moisture during drought. USDA For. Serv. Tech. Notes No. 125.

17. ____. 1938. Deep rooting and plantation survival. USDA For. Serv. Tech. Notes No. 140.

18. ____. 1939. Beneficial effect of partial shade on field survival. USDA For. Serv., Lk. Sts. For. Expt. Sta., Tech. Notes No. 144.

19. ____. 1939. When do jack pine seeds germinate? USDA For. Serv. Tech. Notes No. 149.

20. Arend, J. L., N. F. Smith, S. H. Spurr, and J. W. Wright. 1961. Jack pine geographic variation--five-year results from lower Michigan tests. Pap. Mich. Acad. Sci., Arts, and Letters 46:219-238.

21. Bensend, D. W. 1943. Effect of nitrogen on growth and drouth resistance of jack pine seedlings. Minn. Agric. Expt. Sta. Tech. Bull. 163.

22. Benzie, J. W. 1968. Regeneration of cutover jack pine stands. USDA For. Serv. Res. Note NC-49.

23. ___________. 1977. Manager's handbook for jack pine in the north central states. USDA For. Serv. Gen. Tech. Rpt. NC-32.

24. Beaufait, W. R. 1960a. Crown temperatures during prescribed burns in jack pine. Proc. Mich. Acad. Sci., Arts and Letters. 46:251-258.

25. _____________. 1962a. Some effects of high temperatures on cones and seeds of jack pine. For. Sci. 6:194-199.

26. ______________. 1962b. Procedures in prescribed burning for jack pine regeneration. Mich. Coll. of Mining and Technology Tech. Bull. No. 9.

27. Beaufait, W. R. and R. T. Brown. 1960b. Phyteogeography of a representative jack pine site. Mich. Acad. Sci., Arts, and Letters 47:201-209.

28. Burns, R. M. and E. A. Hebb. 1972. Site preparation and reforestation of droughty, acid sands. USDA Agr. Handbk. 426.

29. Cameron, H. 1953. Melting point of the bonding material in lodgepole pine and jack pine cones. Can. Dep. Res. Dev., For. Br., For. Res. Div., Silv. Leafl. 86.

30. Candy, R. H. 1951. Reproduction on cut-over and burned-over land in Canada. Can. Dep. Res. Dev., For. Br., For. Res. Div., Silv. Resource Note No. 92.

31. Caveney, E. W., Jr. 1969. Reproducing jack pine by the shelterwood method in northern lower Michigan. Unpub. M. S. thesis, Mich. State Univ.

32. Cayford, J. H. 1963. Some factors influencing jack pine regeneration after fire in southeastern Manitoba. Can. Dep. For. Publ. 1016.

33. ____________. 1966. Operational trials of regeneration methods for jack pine in southeastern Manitoba. Can. Dep. For. Pub. 1165.

34. ____________. 1970. The role of fire in the ecology and silviculture of jack pine. Proc. Tall Timbers Fire Ecol. Conf. 10:221-244.

35. Cayford, J. H. and J. M. Jarvis. 1963. Furrowing and sheltering to improve early survival of planted red pine on dry sites, southeastern Manitoba. Tree Planters' Notes 59:21-24.

36. Cayford, J. H., Z. Chrosciewicz, and H. P. Sims. 1967. A review of silvicultural research in jack pine. Can. Dep. For. and Rural Dev., For. Br., Dep. Pub. No. 1173.

37. Chrosciewicz, Z. 1963. The effects of site on jack pine growth in northern Ontario. Can. Dep. For., Publ. 1015.

38. ______________. 1967. Experimental burning for humus disposal on clear-cut jack pine sites in central Ontario. Can. Dep. For. Rural Dev., For. Br., Publ. No. 1181.

39. ______________. 1974. Evaluation of fire-produced seedbeds for jack pine regeneration in central Ontario. Can. J. For. Res. 4:455-457.

40. Cooley, J. H. 1971. Planting technique and care of stock affect survival of planted red pine. USDA For. Serv. Res. Note No. NC-159.

41. ___________. 1972. Site preparation for jack pine on Grayling sands. USDA For. Serv. Res. Note No. NC-138.

42. Darlington, H. T. 1945. Taxonomic and ecological work on the higher plants of Michigan. Mich. State College, Agr. Expt. Sta., Tech. Bull. 201.

43. Day, P. R. 1965. Particle fractionation and particle-size analysis. In C. A. Black (ed.) Methods of soil analysis. Part 1. Agronomy 9:545-566. Am. Soc. of Agron., Madison, Wis.

44. De Bell, D. S. and C. W. Ralston. 1970. Release of nitrogen by burning light forest fuels. Soil. Sci. Soc. Am. Proc. 34: 936-938.

45. Ellis, L. M. 1911. Some notes on jack pine (Pinus divaricata) in western Ontario. Forestry Quart. 9:1-14.

46. Eyre, F. H. 1936. Dispersal of jack pine seed from seed trees and slash. Mich. Acad. Sci., Arts, and Letters Pap. 21:279-384.

47. _________. 1938. Can jack pine be regenerated without fire? J. For. 36:1067-1072.

48. Eyre, F. H. and R. K. LeBarron. 1944. Management of jack pine in the Lake States. USDA Tech. Bull. 863.

49. Harper, R. M. 1918. The plant population of northern lower Michigan and its environment. Torrey Bot. Club, Bull. 45:23-42.

50. Hodges, J. P. and R. L. Scheer. 1962. Soil cover aids germination of pine seeds on sandy sites. USDA For. Serv., Tree Planters' Notes 54:1-3.

51. Hyun, J. O. 1977. Geographic variation of jack pine (Pinus banksiana Lamb.). Proc. Lake States Tree Improvement Conf. 13:107-116.

52. Isaac, R. A. and Johnson. 1976. Journal of the AOAC, Vol. 59. from Anon. 1978. Digestion of plant tissue for determination of total nitrogen and/or phosphorus with Tecator block digestor model DS-40. Tecatopic 4/Rev 1, Tecator, Inc.

53. Isaac, R. A. and J. D. Kerber. 1971. Atomic absorption and flame photometry techniques and uses in soil, plant, and water analysis. In L. M. Walsh (ed.) Instrumental methods for the analysis of soils and plant tissue. Soil Sci. Soc. Am.

54. Jameson, J. S. 1961. Observations on factors influencing jack pine reproduction in Saskatchewan. Can. Dep. For., For. Res. Div., Tech. Note No. 97.

55. ____________. 1963. Relation of jack pine height-growth to site in the mixedwood forest section of Saskatchewan. Can. Dep. For., For. Res. Br., Contribution No. 564.

56. Lambert, J. L., J. R. Boyle, and W. R. Gardner. 1972. The growth response of a young pine plantation to weed control. Can. J. For. Res. 2:152-159.

57. LeBarron, R. K. 1944. Influence of controllable environmental conditions on regeneration of jack pine and black spruce. J. Agr. Res. 68:97-119.

58. LcBarron, R. K. and F. H. Eyre. 1938. The influence of soil treatment on jack pine reproduction. Pap. Mich. Acad. Sci. 23:307-310.

59. Logan, K. T. 1966. Growth of tree seedlings as affected by light intensity. II. Red pine, white pine, jack pine, and eastern larch. Publ. Dep. For. Can. No. 1160.

60. Lopushinsky, W. and G. O. Klock. 1974. Transpiration of conifer seedlings in relation to soil water potential. For. Sci. 20:181-186.

61. Lotan, J. E. 1974. Cone serotiny--fire relationships in lodgepole pine. Proc. Tall Timbers Fire Ecol. Conf. 14:267-278.

62. MacArthur, J. D. 1965. Planting methods to overcome strong competition form dense, herbaceous vegetation. Can Dep. For., For. Res. Br., Contribution No. 638.

63. MacHattie, L. B. and K. W. Horton. 1963. Influences of microclimates on mortality and growth of planted white spruce, jack pine and white pine. Can. Dep. For., For. Res. Br., Contribution No. 511.

64. Maissurow, D. K. 1941. The role fire in the perpetuation of virgin forests of northern Wisconsin. J. For. 39:201-207.

65. Martin, R. E. and L. S. Davis. 1960. Temperatures near the ground during prescribed burning. Proc. Mich. Acad. Sci., Arts and Letters 46:239-250.

66. McCumber, J. E. 1979. Timber management guide for the Huron-Manistee jack pine type. Unpub. Rpt., Huron-Manistee National Forest, USDA For. Serv.

67. Miller, E. L. and G. Schneider. 1971. First year growth response of direct seeded jack pine. Mich. St. Univ., Ag. Expt. Sta. Res. Rpt. 130.

68. ______________________________. 1971. Container-grown jack pine establishment on modified sites in lower Michigan. Mich. St. Univ. Ag. Expt. Sta., Res. Rpt. 137.

69. Mullin, R. E. 1979. Plantation performance averages for jack pine. Ontario Ministry of Nat. Res., For. Res. Note No. 20.

70. Nie, J. O., C. H. Hull, J. G. Jenkins, K. Steinbrenner, and D. H. Bent. 1975. SPSS:Statistical package for the social sciences. (2nd ed.) McGraw-Hill Book Co., New York.

71. Noakes, J. W. 1946. Effect of different methods of slash disposal on jack pine reproduction. Can. Dep. Mines and Res., Lands, Parks, and Forests Br., Silv. Res. Note No. 78.

72. Nordin, J. O. and D. F. Grigal. 1976. Vegetation, site and fire relationships within the area of the Little Sioux fire, northeastern Minnesota. Can. J. For. Res. 6:78-85.

73. Pawluk, S. and H. F. Arneman. 1961. Some forest soil characteristics and their relationship to jack pine growth. For. Sci. 7:160-173.

74. Pereira, J. S. and T. T. Kozlowski. 1977. Water relations and drought resistance of young *Pinus banksiana* and *Pinus resinosa* plantation trees. Can. J. For. Res. 7:132-137.

75. Ralston, R. A. 1951. Successful natural jack pine regeneration. USDA For. Serv., Lk. Sts. Expt. Sta., Tech. Notes No. 363.

76. Rudolf, P. O. 1937. Lessons from past forest planting in the Lake States. J. For. 35:72-76.

77. ____________. 1939. Why forest plantations fail. J. For. 37:377-383.

78. ____________. 1950. Forest plantations in the Lake States. USDA Tech. Bull. No. 1010.

79. ____________. 1958. Silvical characteristics of jack pine. USDA For. Serv., Lk. Sts. For. Expt. Sta., Sta. Pap. No. 61.

80. Schantz-Hansen, T. and R. A. Jensen. 1952. The effect of source of seed on growth of jack pine. J. For. 50:539-544.

81. Schoenike, R. E., T. D. Rudolph, and T. Schantz-Hansen. 1959. Cone characteristics in a jack pine seed source plantation. School of For., Univ. of Minn., Minn. For. Note No. 76.

82. Scholl, D. G. 1966. The effect of prescribed burning on the properties of the Grayling soil series in upper Michigan. Unpub. M. S. thesis, Mich. St. Univ.

83. Severson, R. C., D. F. Grigal, and H. F. Arneman. 1975. Percolation losses of phosphorus, calcium, and potassium from some Minnesota soils. Soil Sci. Soc. Am. Proc. 39:540-543.

84. Shetron, S. G. 1972. Forest site productivity among soil taxonomic units in northern lower Michigan. Soil Sci. Soc. Am. Proc. 36:358-363.

85. ____________. 1974. Distribution of free iron and organic carbon as related to water in some forested sandy soils. Soil Sci. Soc. Am. Proc. 38:359-362.

86. Sims, H. P. 1964. Root development of jack pine seedlings on burned-over dry sites in southeastern Manitoba. Dept. For., Canada, Publ. 1061.

87. _________. 1975. Temperature and moisture conditions on a plowed jack pine strip cut in southeastern Manitoba. Can. J. For. Res. 5:541-545.

88. Sims, H. P. and D. Mueller-Dombois. 1968. Effect of grass competition and depth to water table on height growth of coniferous tree seedlings. Ecology 49:599-603.

89. Smith, D. W. 1970. Concentrations of soil nutrients before and after fire. Can. J. Soil Sci. 50:17-29.

90. Soil Survey Staff. 1976. Grayling series.

91. ________________. 1977. Graycalm series.

92. Soper, E. K. 1919. The peat deposits of Minnesota. Minn. Geol. Surv. Bull. 16.

93. Steel, R. G. D. and J. H. Torrie. 1960. Principles and procedures of statistics. Hill Book Co., New York.

94. Sterret, W. D. 1920. Jack pine. USDA Bull. 820.

95. Tryon, E. H. 1948. Effect of charcoal on certain physical, chemical, and biological properties of forest soils. Ecol. Monog. 18:81-115.

96. Urie, D. H. 1959. Pattern of soil moisture depletion varies between red pine and oak stands in Michigan. USDA For. Serv., Lk. Sts. For. Expt. Sta., Tech. Notes No. 564.

97. Van Wagner, C. E. 1966. Three experimental fires in jack pine slash. Can. Dep. For., Dep. For. Pub. No. 1146.

98. Voss, E. G. and G. E. Crow. 1976. Across Michigan by covered wagon: A botanical expedition in 1888. The Michigan Botanist 15:3-70.

99. Wells, C. G., R. E. Campbell, L. F. DeBano, C. E. Lewis, R. L. Fredericksen, E. C. Franklin, R. C. Froelich, and P. H. Dunn. 1979. Effects of fire on soil. USDA For. Serv. Gen. Tech. Rpt. WO-7.

100. Whiteside, E. P., I. F. Schneider, and R. L. Cook. 1956. Soils of Michigan. Mich. St. Univ. Ag. Expt. Sta. Special Bull. 402.

101. Wilde, S. A. 1964. Changes in soil productivity induced by pine plantations. Soil Sci. 97:276-278.

102. __________. 1966. Soil standards for planting Wisconsin conifers. J. For. 64:389-391.

103. Wilde, S. A., J. G. Iyer, C. Tanzer, W. L. Trautmann, and K. S. Watterston. 1964. Growth of jack pine, Pinus banksiana Lamb., plantations in relation to fertility of non-phreatic sandy soils. Soil Sci. 98:162-169.

APPENDIX A

SCIENTIFIC NAMES OF SPECIES ENCOUNTERED IN THIS STUDY

APPENDIX A

SCIENTIFIC NAMES OF SPECIES ENCOUNTERED IN THIS STUDY

A. Tree and shrub species[1]

1. Alder - *Alnus rugosa* (L.) Gaertn.
2. Aspen - *Populus* spp.
3. Balsam fir - *Abies balsamea* (L.) Mill.
4. Basswood - *Tilia americana* L.
5. Beaked hazel - *Corylus cornuta* Marsh.
6. Black spruce - *Picea mariana* (Mill.) B.S.P.
7. Bur oak - *Quercus macrocarpa* Michx.
8. Eastern white pine - *Pinus strobus* L.
9. Hazel - *Corylus americana* Walt.
10. Jack pine - *Pinus banksiana* Lamb.
11. Lodgepine pine - *Pinus contorta* Dougl.
12. Northern pin oak - *Quercus ellipsoidalis* E.J. Hill
13. Northern red oak - *Quercus rubra* L.
14. Paper birch - *Betula papyrifera* Marsh.
15. Red pine - *Pinus resinosa* Ait.
16. Sugar maple - *Acer saccharum* Marsh.
17. Trembling aspen - *Populus tremuloides* Michx.
18. White spruce - *Picea glauca* (Moench) Voss

[1]Harlow, W. M. and E. S. Harrar. 1969. Textbook of Dendrology (5th ed.). McGraw-Hill Book Company, New York.

B. Ground Cover Species[2]

1. Bearberry - *Arctostaphylos uva-ursi* (L.) Spreng.
2. Blue joint grass - *Calamagrostis canadensis* (Michx.)
3. Blueberry - *Vaccinium* spp.
4. Bracken fern - *Pteridium aquilinum* (L.) Kuhn
5. Bunchberry - *Cornus canadensis* L.
6. Dry land sedge - *Carex pensylvanica* Var. distans Peck
7. False lily-of-the-valley - *Maianthemum canadense* Desf.
8. Fireweed - *Epilobium angustifolium* L.
9. Labrador-tea - *Ledum groenlandicum* Oeder
10. Leatherleaf - *Chamaedaphne calyculata* (L.) Moench
11. Raspberry - *Rubus idaeus* L.
12. Reindeer lichen - *Cladonia* spp.
13. Sand cherry - *Prunus pumila* L.
14. Sedges - *Carex* spp.
15. Sweet-fern - *Comptonia peregrina* (L.) Coult.
16. Twinflower - *Linnaea borealis* L.
17. Wintergreen - *Gaultheria procumbens* L.

C. Insect Species[3]

1. Jack pine budworm - *Choristoneura pinus* Freeman
2. Sawfly - *Neodiprion lecontei* (Fitch)

---

[2]Fernald, M. L. 1950. Gray's Manual of Botany. American Book Company, New York.

[3]Wilson, L. F. 1977. A guide to insect injury of conifers in the Lake States. USDA For. Serv., Ag. Handbk. No. 501.

D. Pathogen species[4]

1. Pine-oak rust - Cronartium quercuum (Berk.)

---

[4] Ibid.

APPENDIX B

UNIT CONVERSIONS

APPENDIX B

UNIT CONVERSIONS

English to Metric

1 inch = 2.540 centimeters
1 foot = 0.3048 meters
1 chain = 20.12 meters
1 acre = 0.4047 hectares
1 pound = 0.4536 kilograms
1 pound/acre = 1.121 kilograms/hectare
1 $foot^2$/acre = 0.2294 $meters^2$/hectare

Metric to English

1 centimeter = 0.3937 inches
1 meter = 3.281 feet
1 meter = 0.04971 chains
1 hectare = 2.471 acres
1 kilogram = 2.205 pounds
1 kilogram/hectare = 0.8921 pounds/acre
1 $meter^2$/hectare = 4.359 $feet^2$/acre