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

By

John David Marshall

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ABSTRACT

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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.

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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.

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[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).

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[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