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Red Oak (*Quercus rubra* L.) Acorn Collection, Nursery Culture and Direct Seeding: A Literature Review

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Red Oak (*Quercus rubra* L.) Acorn Collection, Nursery Culture and Direct Seeding: A Literature Review

by

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ABSTRACT

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The artificial regeneration of red oak by planting or direct seeding is an important method for restoring oak in ecosystems where it has been lost as a result of past management practices. Planting and direct seeding can also be used to supplement natural oak regeneration and to ensure that sufficient oak reproduction is in place when overstories are removed through timber harvests. There has been a substantial amount of research conducted on the nursery production of bareroot and container-grown red oak and the direct seeding of oaks throughout eastern North America. This paper is a review and synthesis of existing information. Recommendations on seed collection, nursery cultural practices, stock quality and direct seeding techniques are presented.

Keywords: red oak, acorn collection, nursery culture, planting practices, direct seeding

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1.0 INTRODUCTION

Historically, the regeneration of northern red oak (*Quercus rubra* L.) in eastern forests has been favored by relatively frequent disturbances such as windstorms and fire. Where disturbances occurred less often, red oak probably formed only a minor component of the overstory because it is not an aggressive colonizer and has difficulty regenerating under dense shade. During the settlement of this region, forest burning and timber harvesting created conditions that favored the establishment, growth and release of red oak advance reproduction and promoted coppice growth from cut stumps (Crow 1988). As a result, stands of red oak became more prominent throughout the Great Lakes-St. Lawrence and Deciduous forest regions in Ontario (Figure 1).

Today, many red oak stands are being successionally displaced by more shade tolerant species. Oak advance reproduction is sparse if present in these forests. Subordinate crown positions are frequently occupied by more shade tolerant species (Johnson 1994a). Effective forest fire suppression since the 1920s (Cwynar 1977, MacKay 1978, Lynham 1985) has promoted the regeneration of shade tolerant species over that of oak. In Ontario, management by single-tree selection has led to the conversion of mixed-species forests containing red oak to less diverse forests dominated by sugar maple (*Acer saccharum* Marsh.), red maple (*Acer rubrum* L.) and beech (*Fagus grandifolia* Ehrh.). Shelterwood cuts designed to release oak advance reproduction have met with limited success (Sander and Clark 1971, McGee 1975, Rudolph and Lemmien 1976, Loftis 1983, Martin and Hix 1988). Consequently, stands with a major red oak component occur most often on drier ridgetops and on sandy or shallow soils (Gordon et al. 1993). Red oak is becoming a minor component of forests on higher quality sites in Ontario. In the absence of disturbances such as fire, oak seems to be a difficult genus to regenerate with traditional silvicultural practices (Hannah 1987).

Figure 1. *Red oak dominated forests often developed after timber cutting and repeated fires in central Ontario at the turn of the century. These three large oak stems are sprouts arising from a common root system. They originated after the death of the parent tree, which was most likely a result of timber harvest.*

Although fire suppression and selection harvesting have contributed to the replacement of oak by other species (Auchmoody and Smith 1993), the renewal of red oak forests is further complicated by irregular seed production and heavy predation of acorn crops. Artificial regeneration of oak has been used to supplement natural regeneration or to reintroduce oak on sites where it once grew (Russell 1973, Johnson 1984a). Thus, the purpose of this report is to provide a sound basis for the artificial regeneration of red oak by reviewing the current knowledge on seedling production and direct seeding of oak.

The review begins with a discussion of the factors that affect the production and quality of seed in oaks. Guidelines are provided for the collection and handling of seed. Stratification requirements of red oak, and seed storage and testing methods are reviewed. Nursery practices for the production of bareroot and container red oak seedlings are discussed. The final section covers topics pertaining to the direct seeding of oak.

2.0 SEED COLLECTION

2.1 Factors Affecting Seed Crop Production

Acorn yield is highly variable and difficult to predict using stand characteristics. Auchmoody et al. (1993) observed significant annual variation in red oak acorn production in northwestern Pennsylvania. They found that neither mean stand diameter nor mean basal area of mature red oak forests was strongly correlated with acorn yield. Further, year-to-year differences in seed yield among red oak stands were also poorly correlated with the cyclical nature of oak flower production. Bumper crops have been produced by red oak stands with an average diameter of 35 cm and a basal area of 16 m^2/ha in Pennsylvania. However, stands with larger mean diameters or basal areas did not necessarily produce larger acorn crops. Auchmoody et al. (1993) concluded that acorn production in red oak was sporadic, infrequent and unpredictable. However, acorn production has been related to individual tree diameter (Johnson 1994b). In general, trees of larger diameter produce more acorns than trees of smaller diameter. For red oak, maximum acorn production occurs when tree diameter at breast height approaches 50 cm, beyond which it declines (Downs 1944). Dominant and codominant trees, with full crowns that receive light on all sides, are the major acorn producers in a stand.

A red oak acorn crop takes three years to mature: flower primordia are initiated in year one, flower ovules are fertilized in year two, and fertilized ovules mature into acorns in year three (Grisez 1975, Sork et al. 1993). Hence, there is ample opportunity for a random event to affect seed production negatively. The weather during the three-year developmental period is one of the most critical factors that affects acorn yield and viability.

The period of fruit maturation is generally believed to be the most sensitive to weather factors. Spring temperatures, the date of the last spring frost during the year of anthesis (flower bloom), and the summer moisture supply appear to be the most important weather variables that influence acorn yield. Acorn production is reduced in years when late-spring frost damages flowers (Sork et al. 1993). The later the date of the last spring frost during anthesis, the lower the production of viable acorns. Dry, desiccating winds during pollen dispersal also reduce fertilization success (Sork et al. 1993). Conversely, wet periods followed by warm temperatures before flower initiation may improve acorn crops (Auchmoody et al. 1993). Warmer spring temperatures during fertilization and ovule maturation lead to larger acorn yields. However, as the season progresses, summer droughts can lower the production of viable acorns.

Climate may not be the only determinant of seed production, because different oak species do not always have comparable acorn production in the same years. Acorn production during the current year appears to be significantly influenced by previous acorn production levels. Sork et al. (1993) observed that seed-crop size during the current year was negatively correlated with the quantity of acorns produced over the previous one, two and three years. Thus, oaks may need to conserve or store resources for one or more years before they can produce large seed crops. Flower abscission occurs on oaks that have insufficient resources for complete development of all fertilized ovules (Sork et al. 1993). Thus, the tendency for red oak to produce bumper seed crops at four-year intervals appears to be an inherent function of red oak physiology. Sork et al. (1993) concluded that variation in acorn production was not governed solely by random weather events but was primarily due to inherent resource allocation strategies related to previous acorn crops. They suggested that red oak may have an inherent four-year seed production cycle in which seed crop production is directly proportional to photosynthate reserves, and that weather factors modify this pattern, causing additional variation in acorn crop production.

2.2 Predation of Acorn Crops

Insect damage to acorns significantly reduces their ability to germinate (Figure 2). Insects attack developing acorns in tree tops and mature acorns on the ground. Marquis et al. (1976) observed that adult weevils of the genus *Curculio* and the moth, *Melissopus latiferreanus* Wlsm., deposit their eggs in developing acorns. Emerging larvae feed on the cotyledons before the acorns fall from the tree. However, acorns can remain viable in spite of the damage done by feeding insects, provided the embryonic axis has not been destroyed (Bonner 1993). Damage to cotyledon tissue alone does not prevent the germination and development of seedlings, but their vigor is decreased.

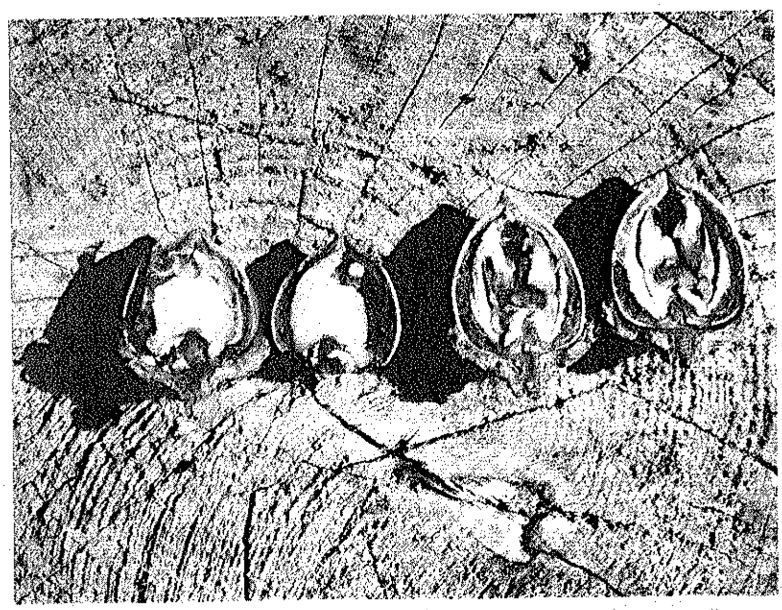


Figure 2. *A variety of insects destroy a significant amount of red oak acorns in Ontario. A substantial portion of these red oak acorns have been damaged by insect larvae. Their quality is low, as is their ability to produce viable seedlings.*

Red oak acorns may use chemical defenses to reduce the amount of seed herbivory. Weckerly et al. (1989) found that tannic acid concentrations in red oak acorns were approximately 20 times greater than in white oak (*Quercus alba* L.). These high concentrations appeared to reduce the number of red oak acorns attacked by larvae of the *Curculio* weevil.

Galford et al. (1991) determined that a variety of insects, including acorn weevils (*Cronotrachelus posticatus* [Boheman]), nitidulids (*Stelidota octomaculata* [Say]), and acorn moths (*Valentinia glandulella* [Riley]), were responsible for killing large numbers of germinating red oak acorns and seedlings during late winter and spring in central Pennsylvania. More recently, millipedes have been identified as significant seed pests of oaks; in particular, the millipede *Ptyoiulus impressus* (Say) feeds on the emerging radicles of acorns in the spring. Galford et al. (1992) reported that approximately 17% of the acorn crop was damaged by millipedes and that *P. impressus* appeared to favor red oak acorns over white. Millipedes were also extremely abundant in depressions of the forest floor where acorns had accumulated in the spring following a bumper red oak acorn crop in the Dufferin County Forest in Ontario (M. Buchanan, Neighbourhood Environmental Studies, Unionville, Ontario, personal observation).

A wide variety of wildlife consumes acorns and can destroy most of the seed crop in years of low to moderate production (Marquis et al. 1976). Deer, bears, turkeys, bluejays, squirrels, chipmunks, voles and mice consume acorns. Despite the large number of acorn predators currently identified, thousands of acorns per hectare can survive predation from insects, animals and birds when large acorn crops are produced (Galford et al. 1992).

2.3 Estimating Acorn Crops

The size of previous acorn crops, weather, genetic variability, and acorn predation cause significant year-to-year and tree-to-tree variation in seed production. These factors make accurate forecasts of acorn crops nearly impossible until shortly before seed-crop maturity (Cecich 1993a,b).

Acorn abundance has traditionally been determined in the fall by sampling acorns on the ground or as they fall from trees (Auchmoody et al. 1993). Acorn caps also may be used to estimate acorn crop production. Auchmoody et al. (1993) reported that acorn crops ranged from a low of 17,300 to as high as 674,600 acorns/hectare per year during a four-year study in northwestern Pennsylvania. Based on this research, Table 1 was devised as a guide to rate crops from ground counts of acorns or acorn caps. However, crop estimates based on fall acorn counts do not account for overwinter losses of acorns to predation, disease, or desiccation. Because these losses can be significant and because not all acorns land in suitable spots for germination, crop size estimates derived from fall counts may not be related to the number of seedlings established in the spring.

The distribution of acorns on the forest floor is highly variable, being influenced by the distribution of acorn-producing oaks and by microtopography. Most acorns fall within a tree-length of the parent tree. Many acorns collect in small depressions on the forest floor and acorns are often concentrated on the downhill side of oaks. Survey methods and sampling designs should account for the variability in acorn distribution when estimating crop sizes from ground counts of acorns or acorn caps.

Table 1. Guide for rating red oak acorn crops based on ground counts of acorns or acorn caps per unit area.

Crop Rating	Number of Acorns/ha (thousands)	Number of Acorns/m^2
Bumper	>600	>60
Good	300-600	30-59
Fair	160-300	16-29
Poor	50-160	6-15
Trace	<50	<5

Table 2. Guide for rating red oak acorn crops from acorn counts on branch terminals.

Seed crop rating	Average number of acorns/60-cm branch tip
Bumper	≥25
Good	17-24
Fair	9-16
Poor	4-8
Trace to None	<3

Red oak acorns mature underneath adjacent leaves and are thus visible from the ground. Acorn seed crops can be estimated using binoculars to view fruit on one-year-old branches (Grisez 1975). Using this approach, approximately 20 to 30 branches from the upper crown of a red oak should be chosen at random, and all acorns along a 60-cm terminal branch (not including the current-year's branch growth) and its branchlets should be counted. The numbers of acorns per 60-cm branch are then averaged. Acorn crops can be classified using Table 2.

2.4 Collection Techniques

Mature acorns can be collected during early autumn before leaf-fall (i.e., late-September to mid-October). Acorns can be collected from the ground, or as they fall using traps or tarpaulins. Collecting acorns in traps may reduce the amount lost to predators provided that the trap is designed to protect acorns from animals and birds. Typical traps are constructed of heavyweight plastic sheeting, approximately 4 X 9 m, and are suspended above the ground so that falling acorns are funnelled into freely draining plastic containers (Sork et al. 1993), or into wire-mesh baskets (Marquis et al. 1976). Frequent collection of acorns from traps will reduce the risk of loss to predators.

The very first acorns to drop in the fall are usually defective, either not fully developed or damaged in some way that makes them unsuitable for collection (Bonner and Vozzo 1987). Acorns can be collected in large quantities from the tops of trees felled during logging, though acorns should be mature or very nearly so when the trees are cut. Immature acorns may continue to ripen after the tree is cut, but once the foliage becomes fully desiccated, ripening stops (Bonner and Vozzo 1987). Immature acorns should not be collected because they cannot be artificially ripened after picking (Bonner 1979).

2.4.1 Seed Source

There is tremendous genetic variability between individual red oak trees and stands of oak (Sander 1990). Seed quality and size have a strong influence on many of the morphological, physiological and growth characteristics of red oak (Teclaw and Isebrands 1991). For example, the number of permanent first-order lateral roots and the total number of roots produced by red oak seedlings are related to seed quality (Schultz and Thompson 1989, Schultz et al. 1989, Coggeshall 1990). Seedling heights and diameters are influenced by red oak genetics through its effect on root system development (Schultz and Thompson 1989). Sowing genetically similar seedlots from superior stands or trees results in the production of uniform stock and allows for more efficient production of nursery stock of acceptable quality than when seeds of mixed parentage or provenance are sown together.

It is important to use local seed sources collected from high-quality red oak phenotypes (Figure 3) for nursery production of seedlings (McElwee 1970, Sander 1982, Stroempl 1985, Crow and Isebrands 1986, Johnson et al. 1986). Selecting seed sources of known quality and growth performance increased percentage germination and uniformity in nursery beds, resulted in significantly greater heights and diameters and improved seedling quality (Crow and Isebrands 1986, Buchschacher et al. 1991, Buchschacher et al. 1993). Collecting seed from unknown seed sources is not recommended (Teclaw and Isebrands 1991).

Unfortunately, unsupervised public collections of acorns are often used to supply hardwood nurseries in the Lake States and New England regions (Crow and Isebrands 1986). In Ontario, most red oak acorns are collected by Ministry of Natural Resources (OMNR) staff, or purchased from contractors. The St. Williams Nursery has begun a program of maintaining formal records of parent tree characteristics and conducting field trials to relate seedling quality to provenance, but most nurseries have not instituted such procedures (T. McDonough, OMNR, Sault Ste. Marie, Ontario and D. Boufford, OMNR, Orono, Ontario, personal communication). Sowing acorns of mixed parentage and provenance results in large variability in the size and quality of red oak stock produced by OMNR nurseries and reduces the proportion of seedlings that meet recommended standards for high-quality oak stock (Gordon 1988; Dey, unpublished data).

Figure 3. *Acorns should be collected from dominant red oaks that exhibit superior phenotypic traits, which include trees with tall, straight boles, good diameter growth rates and well developed crowns.*

2.4.2 Seed Quality

The collection of quality seed requires that acorns be gathered when they are fully mature (Figure 4), because ripening ceases shortly after acorns are separated from the tree (Bonner 1993). The following characteristics of mature acorns have been provided by Bonner and Vozzo (1987) and Bonner (1993):

1. The pericarp of immature acorns is green in color, and turns dark brown to black at maturity.
2. Cups of mature acorns separate easily from the pericarp without being forced and without leaving pieces of the cup attached to the acorn.
3. The cup scar is "bright" in appearance immediately after cup removal. Fresh cup scars for red oaks are commonly bright yellow or orange in color, but these colors fade within a few days after cup removal.
4. A cross-sectional cut of mature acorns shows light creamy white to yellow cotyledons for red oaks.

Defective acorns should be discarded. Common defects or defect indicators include small weevil holes in the pericarp, cracked pericarps, rodent damage, mold, deformed pericarps, black spots on the pericarp (which indicates fungal infection) and acorns with dull-brown cup scars (Lotti 1959, Olson 1974). Fallen acorns with their cups firmly attached are usually defective and should be discarded (Olson 1974). In light crop years, acorn quality is often poor (Bonner and Vozzo 1987) and high proportions of acorns are infested by insects.

During field collection of acorns, a sample from each seed source should be inspected for soundness, maturity and quality by cutting the acorns in half. The acorns should be inspected using the maturity indices noted above, together with an evaluation of insect damage and acorn defects. The cut test gives collectors an approximation of the percentage of mature, sound seed, which can be used to determine if further seed collection is warranted (Figure 4).

Acorns should be collected from the ground soon after they fall from the tree. Wildlife will consume many acorns once they are on the ground. Furthermore, acorn quality can decline rapidly once the acorns are on the ground, especially in dry weather (Teclaw and Isebrands 1986). However, the first acorns to drop in the fall are usually defective and collection should be delayed until the main release of acorns occurs (Johnson and Krinard 1985, 1987).

There is some indication that acorn size can be used to assess acorn quality. Farmer (1980) observed a positive correlation between acorn size and seedling size (i.e., height and leaf area) for red oak, chestnut oak (*Quercus prinus* L.), white oak and bear oak (*Quercus ilicifolia* Wangenh.). Similarly, Kolb and Steiner (1990) noted that red oak seedling biomass and vigor were positively correlated with seed dry mass. Kleinschmit and Svolba (1979) reported a strong positive correlation between acorn weight and height growth of English oak (*Quercus robur* L.) and Durmast oak (*Quercus petraea* [Matt.] Liebl.) in Germany.

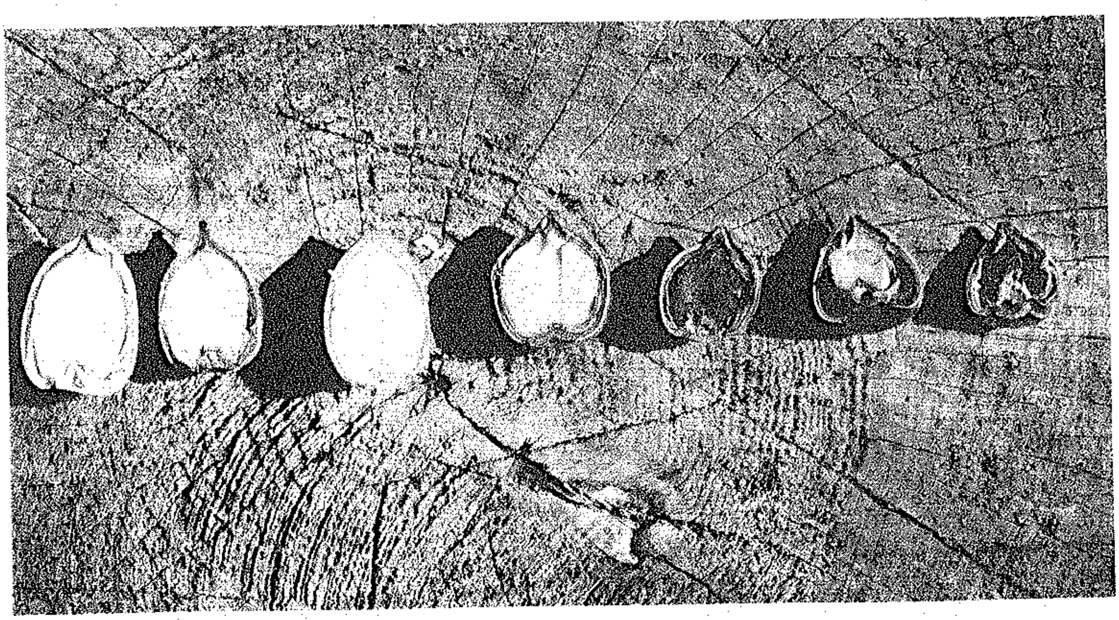


Figure 4. *Collection of fully-developed, sound acorns is a crucial first step in regenerating oak artificially. The cut test can be used to assess seed maturity and quality. The acorns on the left are mature and sound, while those on the right are under-developed and insect-damaged.*

Floating acorns in water is a good method for separating quality acorns from damaged or immature acorns. Sound, mature acorns sink in water (Bonner and Vozzo 1987). However, sound acorns that are initially "dry" may take up to 24 hours to sink. Acorns that continue to float are usually defective or immature, and they have a low germinative capacity (Johnson and Krinard 1985, Crow and Isebrands 1986, Teclaw and Isebrands 1986, Jacobs and Wray 1992, Bonner 1993). Floating acorns should be discarded. Floating acorns with caps attached have little or no germinative capacity (Teclaw and Isebrands 1986). Water flotation of acorns also facilitates the removal of leaves, cups and other debris, which should be done before storage. Some acorns that sink may be weeviled or have cracked pericarps and these should be removed from the collection. After water flotation, some nurseries in the United States treat acorns to kill weevils by immersing them in 49°C water for 40 minutes, or by treating acorns with serafume fumigant (M. Rose, OMNR, St. Williams Nursery, personal communication). Acorns should be kept cool and moist to maintain their quality until they can be sown or placed in overwinter storage.

2.4.3 Seed Moisture

Acorns are recalcitrant, i.e., they do not tolerate desiccation below about 30% moisture content (Korstian 1927, Bonner 1993), thus excessive drying of acorns should be avoided. The moisture content of red oak acorns at maturity is about 40 to 50% (Bonner 1974). Bonner and Vozzo (1987) stated that acorn viability will be completely lost when moisture contents drop below 25% for an extended period of time. Thus, the key to maintaining acorn quality is to avoid any desiccation.

Prompt collection of mature acorns, and proper handling, shipping and storage, reduce the chances of acorn desiccation. Flotation of acorns in water ensures that they have adequate moisture. Acorns should be transported in plastic bags or covered containers to reduce moisture loss (Bonner 1993). Precautions should be taken to keep acorns from overheating in bags or containers, especially in warm, dry weather. Shading acorns and spraying them with water will help to keep them cool and moist. Acorns should be placed in cold storage immediately, even if they will be sown in the same fall (Bonner and Vozzo 1987).

Seed moisture content should be determined when a collection of acorns is first received, before placing acorns in storage or sowing them in the fall, and periodically during long-term cold storage. Individual collections and seedlots should be tested separately. A minimum acorn moisture content can be a criterion used for the determination of payment to contract collectors. Bonner and Vozzo (1987) provided detailed instructions for testing moisture content. Moisture determinations can be made in one day from a small sample of acorns taken from each seedlot. Moisture determination requires a forced-draft oven for drying acorns and a scale for weighing samples.

3.0 SEED STRATIFICATION AND STORAGE

3.1 Stratification of Acorns

Red oak acorns exhibit embryo dormancy and must undergo stratification (cold treatment) before they are able to germinate (Farmer 1974, Bonner and Vozzo 1987). Stratification of red oak requires the application of low temperatures (e.g., 2° to 5°C) to seed in the imbibed state (Roberts 1972). Without stratification, the germinative capacity of red oak acorns can be as low as 40% (Hopper et al. 1985). After stratification for 10 weeks, the germinative capacity of red oak can increase to 90%. Acorns on the forest floor are stratified naturally over the winter and early spring. To stratify acorns artificially, they should be exposed to cold temperatures (2° to 3°C) for 90 days or more (Crow and Isebrands 1986, Teclaw and Isebrands 1986, Bonner and Vozzo 1987), although Olson (1974) recommended using a cold stratification period of 30 to 45 days. Seed moisture contents should be kept high (≥40% based on oven-dry weight) and adequate aeration must be provided during stratification. The stratification requirements for germination of red oak increase with the latitude and the altitude of the provenance (Farmer 1974, Johnson and Krinard 1985, Bonner and Vozzo 1987).

3.2 Storage of Acorns

The conditions used to store acorns for extended periods of time are identical to those used for stratification. In fact, when acorns are overwintered in cold storage, they undergo post-harvest maturation. Acorns should be at maximum moisture content at the start of stratification or cold storage. A minimum acorn moisture content of 30% is suggested for cold storage of acorns. Water flotation for 24 to 48 hours before storage results in acceptable acorn moisture contents (Hopper et al. 1985). Johnson and Krinard (1985) found that 40 to 45% moisture content is a good storage range for southern red oak acorns.

Acorn moisture content should be monitored periodically during storage. If moisture content drops below 35% (based on oven-dry weight) then acorns can be soaked at room temperature until their moisture contents are above 40% (Johnson and Krinard 1985, 1987).

Surface-drying acorns before packaging for cold storage is not essential (Bonner and Vozzo 1987). However, moisture condensation occurs in the bags or containers during storage. When pools of water form in the bottom of containers, they should be drained (Bonner 1993). Surface drying of acorns before placement in cold storage may minimize problems with excessive moisture during long-term storage.

Some researchers have used Sphagnum peat moss, dry sand, moist sand, or dry pine sawdust in bags to improve the maintenance of seed quality during long-term storage (Suszka and Tylkowski 1982, Galford et al. 1992). However, Bonner and Vozzo (1987) have concluded that polyethylene bags without any packing medium work equally well for stratification and long-term storage of acorns. The use of cloth bags for long-term storage of acorns is not recommended because cloth allows excessive drying of acorns (Bonner 1973).

Bonner (1973) observed that the percentage germination of southern red oak species improved as storage temperatures were decreased from 8.3° to 2.7°C. Warmer storage temperatures increased the germination of acorns during storage. Acorns do not survive storage at freezing temperatures (-10°C) (Bonner 1973). It is generally recommended that temperatures be maintained above but near freezing (1° to 3°C) for long-term storage of red oak acorns (Farmer 1975a, Crow and Isebrands 1986, Bonner and Vozzo 1987, Bonner 1993).

Proper storage of acorns requires that containers be permeable to gases because acorns respire during storage (Bonner and Vozzo 1987), and airtight storage containers cause substantial acorn mortality (Bonner 1993). Polyethylene bags of 4- to 10-mil thickness are very suitable for long-term storage because they are permeable to carbon dioxide and oxygen, yet largely impermeable to water (Johnson and Krinard 1985, Teclaw and Isebrands 1986, Bonner and Vozzo 1987, Bonner 1993). Thinner polyethylene bags allow excessive moisture loss and bags thicker than 10 mil restrict gas exchange. Drums, cans or boxes with polyethylene liners are good containers for bulk storage of acorns. However, container tops and liners should not be completely sealed to allow for adequate aeration (Bonner 1993). Bags

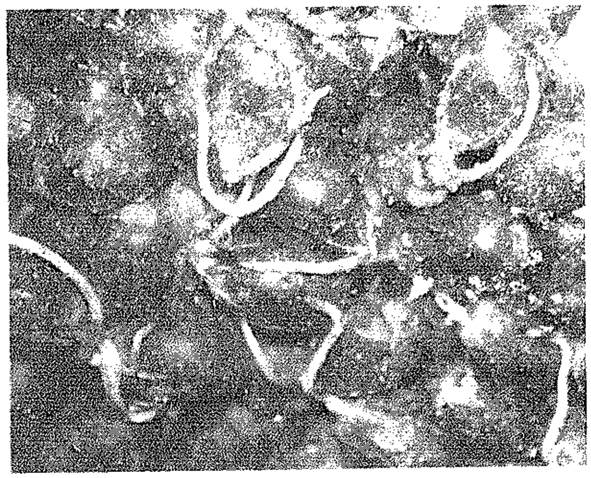


Figure 5. *Red oak acorns may begin germinating over the winter in cold storage.*

should be stored on shelves for good air circulation because storage on the floors of coolers restricts air flow. Wire shelves provide better air circulation than solid wood shelves (Johnson and Krinard 1987, Kennedy 1993). Limiting the amount of acorns in a container improves gas exchange and helps to prevent the buildup of carbon dioxide. Kennedy (1993) recommended storing no more than 9 to 11 kg of seed per bag. Finally, bags should be labeled properly with the date of collection, provenance and percent soundness.

Red oak acorns may begin to germinate during stratification and cold storage, and considerable radicle growth may occur (Figure 5) (Olson 1974, Bonner 1993). Microorganisms may kill radicle tips during storage and radicles may be broken after storage when the acorns are sown (Bonner 1993). Bonner and Vozzo (1987) and Bonner (1993) suggested that this is not a problem because oaks are capable of secondary root development. Broken radicles have not affected red oak seedling production in nursery beds (Bonner 1982, Barden and Bowersox 1990). In fact, damage to the radicle results in a multiple-rooted seedling, which may survive outplanting better than single-rooted seedlings (Bonner and Vozzo 1987).

Microorganisms occasionally develop on acorns in cold storage. Acorns can be sterilized at any time before or during storage by soaking them in a 10% solution of sodium hypochlorite (Dixon et al. 1984) or by rinsing them in captan fungicide to retard mold (Teclaw and Isebrands 1986). As well, insect larvae emerge from acorns to pupate during storage. No special precautions need be taken to prevent further insect damage because the larvae do not attack acorns during storage (Bonner 1993). They usually die during cold storage.

Bonner (1973) has successfully stored southern red oak species without serious loss of acorn viability for up to three years. He found that 60% or more of the acorns remained viable after three years of cold storage. However, acorn quality does decrease with each year of storage and improperly stored acorns lose their viability after as little as one year (Bonner and Vozzo 1987, Bonner 1993, Kennedy 1993). Northern red oak was successfully stored over two winters by mixing the acorns with dry peat or pine sawdust (1:1 by volume) and storing them at -1° to -3°C in metal milk cans (Suszka and Tylkowski 1982). In Ontario, Creasey et al. (1992) stored red oak acorns for one year in a sand and perlite medium at 2° to 5°C. The acorns were floated before storage and moisture contents during the study varied from 32 to 37%. Acorn germinative capacity was high during the first year of storage (≥80%), but storage beyond one year caused a rapid decline in acorn viability. Red oak has been stored in 4-mil polyethylene bags at 1° to 4° C for up to five years when seed moisture contents were maintained at 35% (M. Rose, OMNR, St. Williams Nursery, personal communication).

There are several alternatives to overwinter storage of acorns in coolers. In Europe, English oak acorns have been successfully stored in pits 60 to 100 cm deep (Walkenhorst 1985), with straw or litter placed in the top 20 cm of the pit. Similarly, acorns can be buried in moist, well-drained sand or sand and peat mixtures over the winter (Olson 1974). In Ontario, red oak acorns have been successfully stratified and stored over the winter by placing them in minnow traps or mesh bags that were suspended in a free-flowing, well-aerated stream (D. Deugo, OMNR, Bracebridge, Ontario, personal communication). Fall sowing of acorns avoids the need for overwinter storage in coolers. Natural stratification occurs in the nursery bed or in the field (Crow and Isebrands 1986, Bonner 1993). However, proper storage in coolers provides the greatest control of acorn moisture and temperature conditions, and acorn quality and germinative capacity can be monitored easily when they are stored in coolers. Cooler storage of acorns is also the only practical means of storing acorns for more than one season.

3.3 Seed Testing

Seed testing is done to determine seed quality and maturity, seed moisture content, germinative capacity and germination rate. This information is used to determine the suitability of a seedlot for collecting, sowing and storing. These tests are used to monitor and maintain favorable acorn condition during long-term storage. Tests for the field evaluation of seed quality and maturity include the cut test, float test and Bonner and Vozzo's (1987) maturity indices. Bonner and Vozzo (1987) provided detailed instructions for conducting tests for seed moisture content, germinative capacity and germination rate. Acorns should be tested during collection, and before storage or sowing in the nursery or field. Sowing or storing only high-quality seed minimizes regeneration costs, improves control over nursery seedbed densities, and increases the chances of establishing vigorous seedlings.

The cut test, in which acorns are cut in half to assess embryo and cotyledon condition, may be done during collection, or immediately after floating acorns (Figure 4). However, cut tests are less useful for stored seed because there may be a considerable decline in acorn quality without a corresponding change in cotyledon color (Bonner and Vozzo 1987). An alternative test for quantifying acorn viability is the tetrazolium staining test, which requires the incubation of acorns for 24 hours at 21° to 25°C and the use of 2,3,5-triphenyl tetrazolium chloride. This test can be used on acorns at any time, including those that have been in storage. Procedures for this test are given by Bonner and Vozzo (1987).

Acorn germinative capacity is one factor used to characterize seed quality and is used to calculate sowing rates. It may be assessed simply by providing conditions necessary for the germination of stratified seed (Figure 6) (Bonner and Vozzo 1987). Knowledge of the germinative capacity and germination rate can be used to determine sowing rates and to maintain more uniform seedbed densities. However, laboratory germination tests give higher values than can be expected in the nursery or field. With experience, necessary adjustments can be made to sowing rates. A germination test should be done on each seedlot because the germinative capacity of different seedlots is highly variable (Sander 1982). The germination test cannot be used

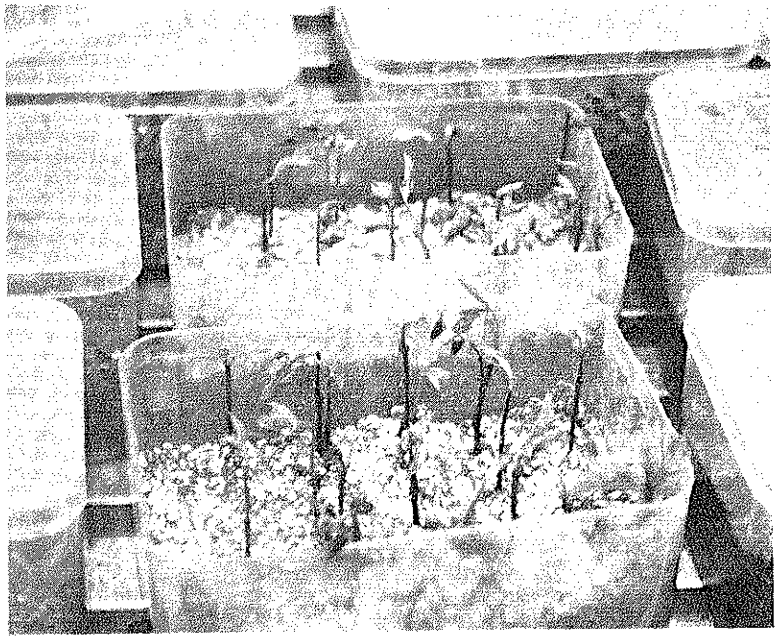


Figure 6. *A germination test is simple to do. It provides valuable information that is used to evaluate seedlot quality and to determine sowing rates.*

on seed that has not been stratified. The viability of fall-collected seed that will be sown before it is stratified should be determined using the cut test on acorns that have been floated. Flotation and sorting of acorns that sink is important in the selection of the highest-quality acorns.

4.0 BAREROOT CULTURE

4.1 Stock Quality

Nursery cultural practices influence the physical characteristics of planting stock, as well as their field survival and growth performance. Exposure to environmental extremes, and competition for sunlight, moisture and nutrients, can stress seedlings planted in clearcuts or in shelterwoods. Well-defined stock quality standards are therefore needed to design and develop cultural practices that produce competitive seedlings efficiently and economically. Seedling root-system characteristics, stem diameter near the root collar, shoot length and other shoot characteristics have traditionally been the focus of nursery stock quality assessment.

4.1.1 Root Characteristics

The survival and growth performance of outplanted red oak depends on a well-developed root system with large carbohydrate reserves, a balanced root:shoot ratio, and a well-branched root system with a framework of permanent lateral roots (Figure 7) (Farmer 1975b; Johnson 1981a, 1989; Crow and Isebrands 1986; Schultz 1990; von Althen 1990; Pope 1993). Farmer (1978) observed that oak root systems are major sinks for carbohydrates, especially starch. However, more work is needed to define critical starch levels for red oak planting stock.

The number of permanent first-order lateral roots that a seedling has when lifted from the nursery is strongly related to its field survival and early growth performance (Kormanik 1986, Kormanik and Muse 1986, Ruehle and Kormanik 1986, Kormanik and Ruehle 1987). Lateral roots that are less than 1 mm in diameter are often lost during lifting, grading, shipping and planting (Perry 1982,

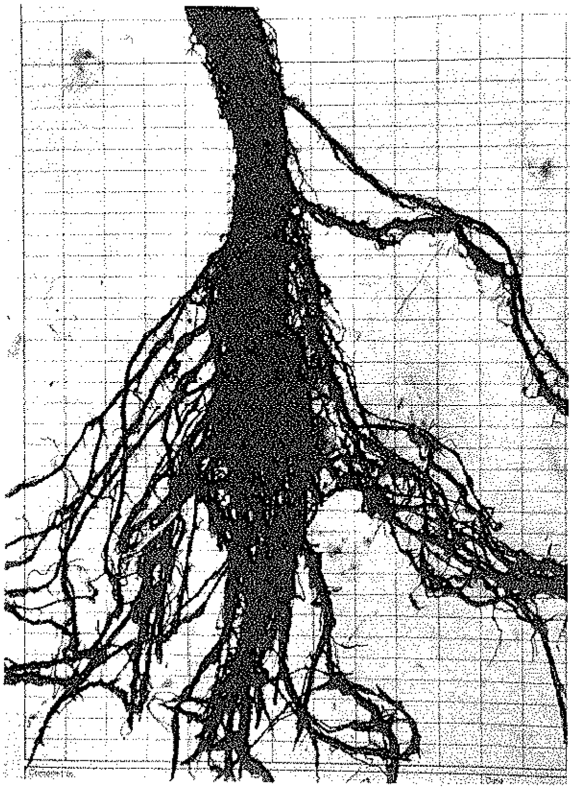


Figure 7. *The size, structure and vigor of oak root systems influences seedling performance after outplanting. This undercut 1-0 red oak root system was produced in an Ontario nursery. It is large and has an abundance of permanent first-order lateral roots.*

Kormanik 1986, Schultz and Thompson 1987, Schultz 1988). Lateral roots greater than 1 mm in diameter are more likely to persist through all nursery and outplanting activities and hence, they can be considered permanent (Thompson and Schultz 1989).

For red oak bareroot stock, survival, height and diameter growth, leaf area, and biomass accumulation increases as the number of permanent first-order lateral roots increases (Crow and Isebrands 1986; Schultz and Thompson 1989, 1993; Schultz et al. 1989; Thompson and Schultz 1989, 1993; Schultz 1990; Bardon and Countryman 1993). It is generally recommended that red oak bareroot stock should have at least five or six permanent first-order lateral roots for acceptable survival and growth performance. However, Kaczmarek (1991) and Kaczmarek and Pope (1993a) were unable to detect a direct relationship between red oak outplanting performance and the number of such roots. Kaczmarek and Pope (1993a,b) concluded that red oak seedling growth cannot be accurately predicted based solely on the number of permanent first-order lateral roots. Although they recognized the importance of these roots, they suggested that the number of first-order lateral roots should not be the sole criterion in evaluating seedling quality.

4.1.2 Stem Diameter

Oak regeneration failures are often the result of planting insufficiently large nursery stock (Johnson 1981a). Although site selection and competition control are important, the success of planted hardwoods is significantly related to initial seedling size for all classes of nursery stock (e.g., 1-0, 1-0, 1-1, container), whether seedlings are undercut, shoot-clipped, or not (Johnson 1994a). Johnson (1989) stated that although many factors are used to describe stock quality, no one is more important for hardwoods than stock size. Many authors have recognized the importance of planting large-diameter seedlings to increase the probability that seedlings will grow to be codominant or larger (McElwee 1970; Farmer 1975a; Johnson 1979, 1981a, 1985, 1992; Zaczek et al. 1993).

Stem diameter near the root collar seems to be a useful grading standard for oaks and this may be related to its correlation with root morphology, root mass and the number of permanent first-order lateral roots (Kormanik 1986, Johnson 1989, Schultz et al. 1989). Kaczmarek and Pope (1993a) found that red oak seedling diameter was positively correlated with the number of first-order lateral roots and concluded that red oak seedling size is more significant than the numbers of such roots in determining outplanting performance.

Johnson (1984a) used the concept of success probabilities to relate nursery practices, stock type and initial seedling size to the survival and growth performance of red oak stock planted in clearcuts and shelterwoods. Seedlings were classed as successful if their net height increment exceeded a threshold average net height increment. Based on this analysis, success probabilities were used to construct Table 3, which presents the number of planted trees needed to obtain one successful tree when red oak is underplanted in shelterwoods. As the initial shoot diameter measured 2.5 cm above the root collar increases, fewer trees must be planted to produce one successful tree after the final removal of the shelterwood. For example, 9.1 red oak 1-0 seedlings must be planted to produce a successful tree when initial stem diameters are 6.4 mm, but only 3.4 seedlings are needed when initial diameters are 11.1 mm. The benefits of planting 1-1 transplant stock are also demonstrated in Table 3. Although the use of 6.4-mm-diameter 1-0 stock requires 9.1 planted seedlings to produce a single successful tree, the use of similar-sized 1-1 transplants requires only 5.9 planted trees.

Johnson (1992) modified the use of success probabilities by changing the success criterion to a percentage of the mean height of the dominant and codominant competitors. For example, if the success criterion is set at 80% of the height of dominant and codominant competitors at a given stand age, then only planted seedlings that grow taller than the success criterion are considered successful. This approach is more reasonable because it relates red oak seedling growth to the growth of its competitors, rather than evaluating seedling performance based on growth alone. The results of this analysis are presented in Table 4 for 1-1 transplants and 2-0 red oak underplanted in a shelterwood. Again, note that the number of planted trees needed to obtain one successful seedling decreases with increasing initial seedling diameter near the root collar.

There have been a variety of recommendations for stem diameter near the root collar as a grading standard for red oak nursery stock. Although a few authors have reported that stock with a stem diameter as small as 5.6 to 6.4 mm is acceptable for outplanting (Russell 1971, Schultz and Thompson 1989), most recommended larger stock. In Ontario, Stroempl (1985) classified large stock as having root collar diameters between 7.4 and 8.5 mm and recommended culling stock less than 4.5 mm in diameter. Von Althen (1990) preferred using 8-mm-diameter or larger stock measured 2 cm above the root collar for planting in Ontario, and considered 6 mm to be a minimum. Others have recommended 8 mm stem diameters (approximately 2 cm above the root collar) (Foster and Farmer 1970, Johnson 1981a), 10 mm (Johnson 1984a, Pope 1993, Smith 1993), and 12.7 mm (Johnson 1984a, Johnson et al. 1986). Johnson et al. (1986) stated that red oak less than 10 mm in diameter (2.5 cm above the root collar) should be culled on the premise that larger stock are more likely to result in successful regeneration of red oak and hence, fewer seedlings must be planted.

Table 3. Number of planted northern red oak trees needed to obtain one successful tree two years after shelterwood removal[1].

Initial shoot diameter[2] (mm)	Planted trees needed to obtain one successful tree (no.)
1-0 and 2-0 Seedlings	
6.4	9.1
7.9	5.9
9.5	4.3
11.1	3.4
12.7	2.9
14.3	2.6
15.9	2.4
1-1 Transplants	
6.4	5.9
7.9	3.7
9.5	2.6
11.1	2.1
12.7	1.9
14.3	1.7
15.9	1.6

[1] From Johnson (1984a). Numbers are for nursery stock with clipped tops and roots pruned 20 cm below the root collar, underplanted in shelterwoods at 60% overstory stocking (according to Gingrich 1967), with a preplanting herbicide application. The shelterwood was removed after three growing seasons.

[2] Shoot diameter is measured at 2.5 cm above the root collar.

Table 4. Number of 1-1 or 2-0 undercut seedlings needed to obtain one codominant or larger tree 5 years after shelterwood removal with and without herbicide treatment[1] (from Johnson 1992).

Initial shoot diameter[2] (mm)	Planted trees needed to obtain one codominant tree or larger	
	Treated with herbicide[3]	Not treated with herbicide
6.4	3.42	5.52
7.9	2.58	3.95
9.5	2.11	3.08
11.1	1.83	2.55
12.7	1.64	2.20
14.3	1.51	1.96
15.9	1.42	1.78

[1] Based on success probabilities for 1-1 stock clipped 15 cm above the root collar and underplanted in a shelterwood for three years.

[2] Measured 2.5 cm above the root collar.

[3] Based on Tordon RTU application on cut stems greater than or equal to 12.7 mm dbh and on stumps of overstory trees.

4.1.3 Shoot Length

One measure of seedling size that is often used to grade stock is shoot length. In a comparison of red oak stock types planted in a clearcut, Wendel (1980) found that seedlings that were initially taller performed the best after outplanting. Recommended shoot lengths for red oak bareroot stock vary from 30 to 45 cm (McElwee 1970, Schultz and Thompson 1989, Pope 1993) to 50 cm (Foster and Farmer 1970, Farmer 1975a, Johnson 1981a). For 2-0 red oak stock, Stroempl (1985) classified seedlings with 55- to 75-cm shoot lengths as large, and those with 30- to 45-cm lengths as small. In Ontario, von Althen (1990) recommended a shoot length of 50 cm for red oak and set 30 cm as a minimum. Kaczmarek and Pope (1993a) found that the initial height of 1-0 red oak was positively correlated with the number of first-order lateral roots and concluded that height was a better indicator of seedling growth after outplanting than was the number of these roots.

4.1.4 Stock Age

Stock age influences the growth performance of outplanted hardwood nursery stock. Steiner et al. (1990) have shown that 2-0 red oak seedlings perform better than 1-0 seedlings after planting. Many researchers recommend planting large 2-0 red oak stock. Although stock age is correlated with outplanting success, the size of nursery stock is more important than stock age as a measure of stock quality (Russell 1971, von Althen 1990). Two-year-old seedlings outperform 1-0 seedlings because they generally are larger and have better developed root systems.

4.1.5 Other Shoot Characteristics

Stroempl (1985) has provided guidelines for assessing the shoot characteristics of red oak nursery stock. Desirable seedlings have a sturdy, straight, single-stemmed shoot with short branches on the previous year's growth. Less desirable seedlings have long branches and multiple leading shoots. Seedlings with thin, whip-like stems grow slowly when outplanted. Multiple-stemmed seedlings should be culled. Desirable seedlings have numerous buds, especially on the previous year's growth, and have a cluster of terminal buds.

4.1.6 Ontario Stock Quality

Gordon (1988) reported that there is large variability in the size and quality of red oak stock produced in Ontario (Figure 8). The 1-0 red oak he underplanted in an Ontario shelterwood had root collar diameters averaging 6.7 mm and shoot lengths of 24 cm, and his 1-1 oak transplants were slightly larger (7.8-mm root collar diameter and 45-cm shoot length). Gordon's observations are supported by Dey's unpublished data, for red oak planted during the spring and fall of 1993 in the Bancroft and Bracebridge areas (Table 5). Dey found that average stem diameters (2.5 cm above the root collar) of undercut 2-0 red oak ranged from 6.4 mm in Bancroft to 8.1 mm in Bracebridge. Seedling diameters were quite variable; for example, they ranged from 1.5 to 17.8 mm in the Bancroft District planting. Shoot lengths of undercut 2-0 red oak averaged 37 cm and ranged from 9.9 to 98.1 cm. The average 2-0 red oak seedling had seven to eight permanent first-order lateral roots, but numbers ranged from zero to 26. The numbers of first-order lateral roots of undercut 1-0 red oak were similar to those for 2-0 stock. However, 1-0 stock was shorter and had slightly smaller stem diameters than 2-0 stock. In general, red oak stock produced in Ontario is highly variable in size and quality, and diameters and shoot lengths do not meet the standards recommended for red oak by others (Foster and Farmer 1970; Farmer 1975a; Johnson 1981a, 1984a; Stroempl 1985; von Althen 1990; Pope 1993; Smith 1993). However, Ontario red oak nursery stock that have been undercut have sufficient numbers of permanent first-order lateral roots based on the recommendations of Thompson and Schultz (1989, 1993) and Schultz and Thompson (1993).

Figure 8. *There is much variation in the quality of red oak stock produced in Ontario nurseries. Seedlings from the same seedlot and grown in the same nursery beds vary significantly in height and diameter.*

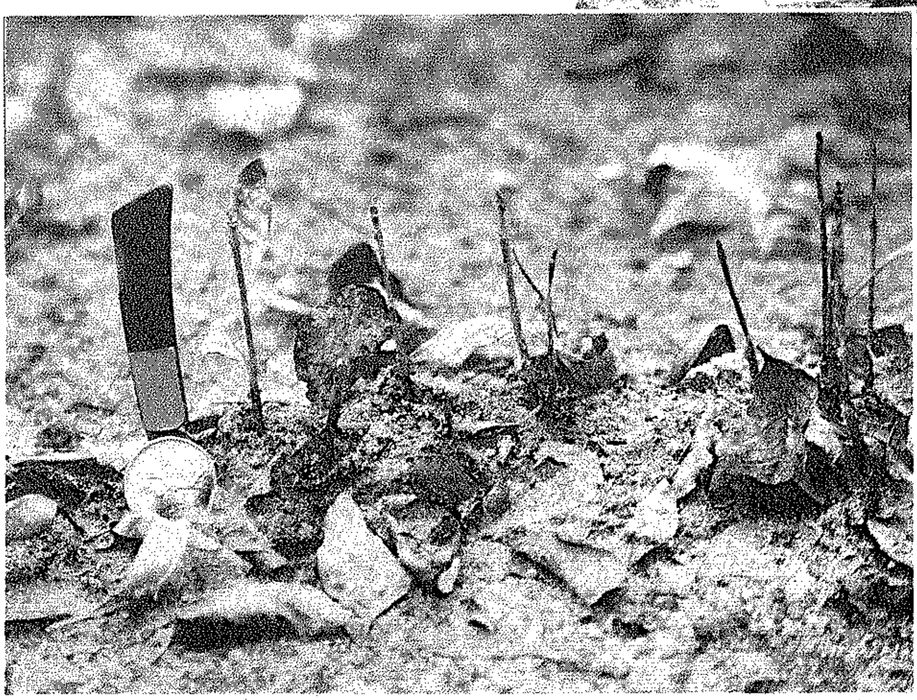


Table 5. Summary statistics for northern red oak stock produced in Ontario nurseries and outplanted in 1993.[1]

Stock Type	Variable	N	Min.	Max.	Mean	Std Dev.
Bracebridge undercut 2-0	Height[2] (cm)	750	9.9	98.1	37.4	12.3
	Diam.[3] (mm)	750	3.9	16.3	8.1	1.83
	FOLR[4]	750	0.0	21.0	7.1	3.1
Bancroft undercut 2-0	Diam.[3] (mm)	7634	1.5	17.8	6.4	1.5
	FOLR[4]	1443	0.0	26.0	8.4	4.0
Bracebridge undercut 1-0	Height[2] (cm)	928	2.5	37.0	18.0	4.8
	Diam.[3] (mm)	928	2.6	10.0	6.16	1.1
	FOLR[4]	928	0.0	31.0	11.2	5.6

[1] D. Dey, unpublished data

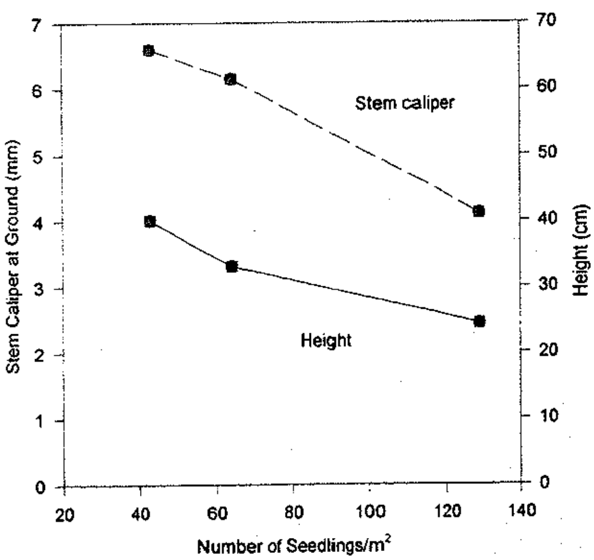
[2] Shoot length measured from the root collar to the base of the furthest live bud.

[3] Diameter measured 2.5 cm above the root collar.

[4] Permanent first-order lateral roots (FOLR) greater than 1 mm in diameter.

Figure 9. *Seedbed density influences stock quality and uniformity of seedling characteristics. Evenly spaced oaks at low seedbed densities (e.g., 32 to 86 seedlings/m²) have larger root systems, more permanent first-order lateral roots and larger stem diameters than seedlings grown at higher densities.*

Figure 10. *Size of 1-0 red oak seedlings in relation to nursery bed density (adapted from Taft 1966).*



4.2 Seedbed Density

The nursery grower has a wide range of cultural practices available that can be used to produce more uniform stock of acceptable quality. One practice that has a strong influence on stock quality and the uniformity of stock characteristics is the regulation of seedbed density (Figure 9). Growing red oak at uniform spacings and lower seedbed densities (e.g., 32 to 86 seedlings/m²) produces a high percentage of plantable seedlings and few culls (Barham 1980, Crow and Isebrands 1986). Red oak seedlings grown at lower seedbed densities have more permanent first-order lateral roots and larger root systems than seedlings grown at higher densities (Crow and Isebrands 1986, Schultz et al. 1989, Schultz 1990, Schultz and Thompson 1993). Lower seedbed densities also result in taller and larger diameter red oak seedlings (Figure 10) (Taft 1966, Barham 1980, Johnson 1981a, Wichman and Coggeshall 1984, Schultz et al. 1989, Schultz 1990, Teclaw and Isebrands 1991, Buchschacher et al. 1993, Schultz and Thompson 1993). Recommended seedbed densities for red oak range from 32 to 86 seedlings per m^2 (Taft 1966, Barham 1980, Hodges and Elam 1984, Wichman and Coggeshall 1984, Schultz et al. 1989).

Using float-tested, high-quality seed decreases the need to oversow, which is done to compensate for poor-quality seed with low germinative capacity. The determination of germinative capacity before sowing is important information for calculating sowing rates. Sowing seed of unknown origin, quality and germinative capacity makes it impossible to obtain uniform seedling densities (Figure 11). Sowing quality seed of known germinative capacity results in more uniform spacing in the seedbed, better control over seedbed density, fewer understocked areas in nursery beds, and a reduced need to thin overstocked clumps of seedlings.

4.3 Undercutting

Undercutting red oak resulted in seedlings with higher potentials for survival and better early growth after outplanting than with uncut seedlings (Schultz et al. 1989). Undercutting 1-0 and 2-0 red oak significantly increased the survival of seedlings planted in shelterwoods or clearcuts (Johnson 1988, 1990; Schultz et al. 1989; Coggeshall 1990; Weigel 1993; Zaczek et al. 1993). Johnson (1988) observed that undercut 2-0 red oak planted in clearcuts had greater root mass, root surface area, leaf mass and leaf surface area than uncut seedlings. The height growth of undercut red oak was also greater than that of uncut seedlings in clearcuts and shelterwoods (Johnson 1988, 1990; Weigel 1993; Zaczek et al. 1993).

Undercutting red oak in the nursery bed is done to increase the number of permanent first-order lateral roots, to increase root mass, and to create a more fibrous root system (Figure 7) (Johnson 1981a, 1988, 1990; Schultz et al. 1989; Coggeshall 1990; Schultz 1990; Schultz and Thompson 1993). Undercutting increases the diameter of lateral roots above the root cut and results in the production of wound roots at the cut surface (Schultz et al. 1989). Wound roots persist after outplanting and function as well as original lateral roots. Thus, undercutting increases the number of potential sites for new root regeneration, which increases the survival and growth performance of outplanted oak (Schultz and Thompson 1989).

Figure 11. *Sowing seed of unknown origin often results in highly variable seedbed densities, reductions in seedling quality and unused growing space in nursery beds.*

Seedling height and diameter growth are both reduced in the year that undercutting occurs (Johnson 1989, Schultz et al. 1989, Schultz and Thompson 1993). It is unlikely that the heights and diameters of 1-0 undercut red oak will approach the sizes used to define quality stock (i.e., 8- to 10-mm root collar diameter and 50-cm shoot length). Therefore, it will be necessary to hold stock over for a second year in the nursery to realize the benefits of both large stock size and increased numbers of first-order lateral roots (Johnson 1994a). Zaczek et al. (1993) evaluated the field performance of various red oak stock types (e.g., 1-0, 2-0, 1-1, 2-1) that had received combinations of undercutting, and shoot clipping, including no cutting or clipping treatments. They found that undercut 2-0 seedlings performed the best three years after planting in a clearcut. Both Smith (1993) and Johnson (1988) recommended using 2-0 red oak stock that has been undercut during its first year in the nursery.

Within any given year, the timing and frequency of undercutting affects the production of first-order lateral roots (Schultz and Thompson 1989, Schultz et al. 1989). Undercutting later in the summer and more frequent undercutting increase the number of first-order lateral roots. Several researchers provide various guidelines for timing the undercutting treatment. Schultz and Thompson (1989), Johnson (1989) and Buchschacher et al. (1991) recommended undercutting red oak after the second flush was complete (Quercus Morphological Index (QMI)=2Lag; Hanson et al. 1986), when the terminal bud has stopped expanding and the uppermost leaves have expanded to about 3/4 size. Johnson et al. (1986) stated that the best time to undercut is just after full leaf expansion of the first flush of growth (QMI=1Lag). Crow and Isebrands (1986) suggested undercutting 10 days after full leaf expansion (QMI=1Lag) rather than later in the summer to maximize the production of first-order lateral roots. When producing 1-0 stock, undercutting should be done when the average shoot has almost reached the desired height because undercutting inhibits further flushing that year, thus reducing subsequent height growth (Johnson 1981a, Schultz and Thompson 1989). However, enough time must be provided before lifting for roots that resulted from wounding of the taproot to suberize and become permanent structures. Approximately 6 to 7 weeks are needed after undercutting for new roots to develop into permanent roots (Schultz and Thompson 1989). This is of less concern when producing 2-0 stock.

The depth of undercutting should be less than the lifting depth so that the roots that result from cutting the taproot and larger lateral roots remain attached to the seedling. Because lifting is commonly done at depths of from 20 cm to 30 cm, undercutting should be done between 13 cm and 15 cm (Johnson et al. 1986, Johnson 1989). Irrigating just before and immediately after undercutting reduces seedling moisture stress (Schultz and Thompson 1989). Seedling water stress can also be reduced by undercutting on cool, moist days.

4.4 Lifting

Red oak stock can be lifted in either the fall, after seedlings become dormant, or in the spring, before they break dormancy. Fall-lifted stock can be stored over the winter or planted immediately. Fall-planted seedlings may experience severe shoot dieback (Johnson 1981c). Fall-lifted stock that has sustained shoot dieback often has delayed root growth and reduced growth capacity as well as reduced shoot growth (Johnson 1979, 1981a). Frost-heaving of fall-planted seedlings may occur in late winter and early spring, although this may be less of a problem for seedlings planted under a shelterwood or on sandy soils.

Spring lifting and planting of oak avoids the problems associated with overwinter storage or fall planting (i.e., shoot dieback, water stress, frost-heaving). Spring-lifted stock is usually in better physiological condition than fall-lifted stock that has been overwintered in cold storage or in nursery heel-in beds (Webb and von Althen 1980, Pope 1993). Root and shoot growth of spring-lifted stock begins earlier in the spring than for fall-lifted stock (Johnson 1981a). Therefore, spring lifting is recommended (Johnson et al. 1986).

4.5 Root Pruning

Root pruning facilitates planting and reduces the temptation to curl roots to fit them into the planting hole, especially on shallow-soiled sites. Severed taproots and permanent first-order lateral roots are primary sites for root regeneration (Johnson et al. 1984). Pruning roots vertically to a length of 20 cm or more does not reduce seedling growth in the nursery (Beckjord and Cech 1980). It is recommended that if roots must be pruned, it be done at the time of lifting. Roots should be trimmed to a vertical length of 20 to 25 cm and a horizontal length of 15 cm (Larson and Whitmore 1970; Russell 1971; Johnson 1981a, 1988; Johnson et al. 1986; Jacobs and Wray 1992; Zaczek et al. 1993).

4.6 Storage

Fall-lifted stock can be overwintered in cold storage or in heel-in beds in the nursery (Figure 12). In Ontario, most red oak is overwintered in heel-in beds. Seedlings overwintered in heel-in beds often experience severe shoot dieback, possibly due to water stress (Johnson 1979, 1981a). The physiological quality of these seedlings is reduced and this is often associated with poor root growth following planting (Webb and von Althen 1980, Johnson 1981a).

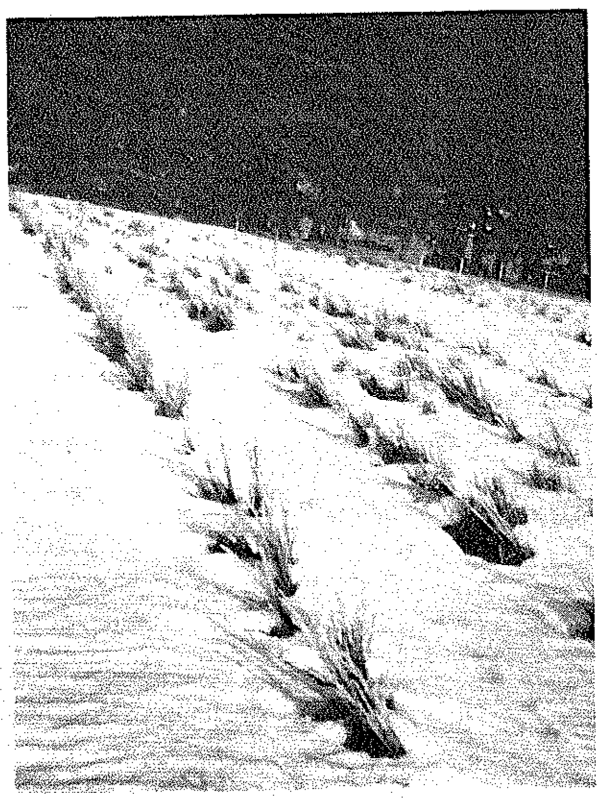


Figure 12. *Red oak stock is commonly lifted in the fall and overwintered in heel-in beds in Ontario. This practice is the least favorable method of storing stock over winter. It is better to overwinter the stock in cold storage or to lift the seedlings in the spring.*

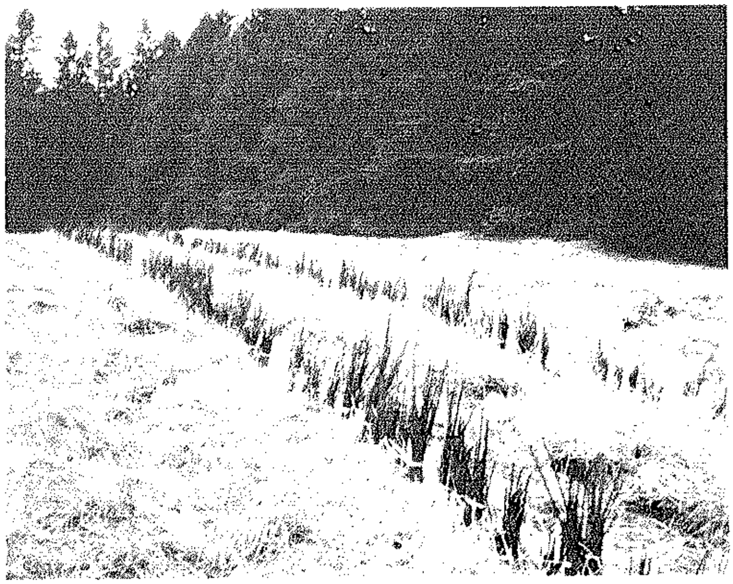


Figure 13. *Seedlings overwintered in heel-in beds are subject to root damage from freezing temperatures and extreme temperature fluctuations. This damage reduces the physiological quality of seedlings, increases the extent of shoot dieback and decreases outplanting performance. Mulching heel-in beds with 25 cm or more of straw or sawdust effectively insulates seedling root systems from severe winter temperatures.*

In Ontario, the roots of fall-lifted red oak overwintered in heel-in beds can become infected with *Fusarium* spp. (D. Dey, unpublished data). *Fusarium* can cause significant root mortality and can reduce seedling survival after outplanting. *Cylindrocladium floridanum* Sob. & C.P. Seym. (a root rot agent) and *Cylindrocarpon destructans* (Zins.) Scholt. also have been isolated from the roots of red oak seedlings overwintered in Ontario nursery heel-in beds. *Fusarium* and *Cylindrocarpon* are probably secondary invaders that are favored by the deteriorated condition of red oak roots (G. Halicki Hayden, OMNR, Sault Ste. Marie, Ontario, personal communication). Reductions in seedling quality due to infections by root rot fungi (e.g., *Cylindrocladium* spp.) have also caused serious losses of black walnut (*Juglans nigra* L.) nursery stock grown and overwintered in Ontario nurseries (S. Greifenhagen, OMNR, Sault Ste. Marie, Ontario, personal communication). Fungal infection appears to occur during the growing season in seedbeds but the deterioration of root systems is apparently aggravated in heel-in beds, where roots are injured by freezing winter temperatures and the extreme temperature fluctuations typical of late winter and early spring. Root damage is more extensive during cold winters with little snow cover. Root deterioration can be reduced by (1) storing bareroot stock over the winter in cold storage at 3°C, (2) treating seedling roots with fungicides before overwinter storage, or (3) mulching heel-in beds (Tisserat and Kuntz 1984, Green 1985). Mulching heel-in beds with straw or sawdust is an effective method of reducing damage to roots (Figure 13) (S. Greifenhagen, OMNR, Sault Ste. Marie, Ontario, personal communication). Temperatures of heel-in beds can be kept above freezing when 25 cm or more of mulch is used. However, overwinter storage of seedlings in nursery heel-in beds is no longer recommended because of the potential problems (Pope 1993).

Cold storage of seedlings over the winter permits better control over temperature and moisture conditions than other storage methods. However, improper cold storage can still cause water stress, severe shoot dieback and reduced physiological quality (Webb and von Althen 1980, Johnson 1981a). Fall-lifted stock should be completely enclosed in polyethylene-lined kraft bags (Webb and von Althen 1980). Seedlings should be stored at 0.5° to 2°C with 70 to 85%

relative humidity (Webb and von Althen 1980, Johnson et al. 1986, Pope 1993). Under this storage regime, xylem water potentials can be three to five times greater (i.e., less negative) than in unprotected stock or in seedlings wrapped in burlap.

The protection of buds during storage, both physically and physiologically, is necessary to ensure good growth following outplanting (Johnson and Rogers 1982). Seedling buds are the source of plant growth regulators that play an important role in the initiation of root and cambial growth in oaks (Wareing 1951, Lee et al. 1974, Farmer 1975b, Pope 1993). Buds also determine future leaf area and photosynthetic potential.

4.7 Shoot Clipping

Shoot clipping has been widely tested as a means to improve the early performance of planted red oak. The effects of shoot clipping on survival and growth of red oak vary considerably. Shoot clipping at about 20 cm above the root collar at the time of planting has increased survival for up to 5 years after clearcutting or shelterwood harvest, regardless of stock type (e.g., 1-0, 1-1, 2-0, container) (Johnson 1984a, 1988, 1990; Johnson et al. 1986; Weigel 1993). Shoot clipping seems to benefit larger-caliper stock more than smaller seedlings, perhaps by restoring a balance between roots and shoots (Steiner 1983; Johnson 1984a, 1989; Kaczmarek and Pope 1993a). The best outplanting performance (i.e., survival and height growth) is often obtained by shoot-clipping and undercutting large-caliper red oak (Toliver et al. 1980; Johnson 1981a, 1984a, 1988, 1990; Johnson et al. 1986). Other researchers have reported no clear positive effect of shoot clipping on the performance of red oak, regardless of stock type (Russell 1971, 1973, 1979; Johnson 1984a, 1988, 1989; Crunkilton et al. 1989; Gordon et al. 1993; Weigel 1993; Zaczek et al. 1993). Shoot clipping can reduce new root growth, shoot growth and leaf area of red oak (Farmer 1975b, Larson 1975, Johnson 1979, Wendel 1980, Johnson et al. 1984, Crunkilton et al. 1988).

The ideal time to shoot-clip red oak is unknown. However, most authors recommend that it be done as close to the planting day as possible because clipping in the spring at the time of planting provides the greatest opportunity for the transport of growth regulators from the shoot to the roots before the buds are removed by clipping (Johnson et al. 1984, 1986; Johnson 1984a, 1988, 1990; Steiner et al. 1990; Zaczek et al. 1993). Translocation of growth-regulating substances from shoot buds to the root system is important for the initiation of new root growth. Though carbohydrate export to roots is completed in early fall, movement of growth hormones continues for some time afterwards (Larson 1978).

4.8 Fertilization and Irrigation

Proper fertilization and irrigation of red oak nursery stock is needed to produce high-quality stock that is in good physiological condition. Large stock in poor physiological condition do not perform well after outplanting (Johnson 1981a). Recommended soil fertility standards for red oak are presented in Table 6. Because nitrogen stimulates shoot flushing (Gall and Taft 1973, Farmer 1975a), frequent application of nitrogen, as urea or ammonium nitrate, applied over the growing season is more beneficial than single applications (Ingram and Joiner 1982, Crow and Isebrands 1986). Maintenance of the proper soil pH (5.0 to 6.0) is also needed for the production of high-quality seedlings (Buchschacher et al. 1991).

Nursery beds should be kept moist but not wet throughout the growing season (Crow and Isebrands 1986). Oak seedling growth is sensitive to minor droughts, and soil water potentials of -600 kPa can inhibit flushing and root growth in oaks (Larson and Whitmore 1970, Larson 1974, Teskey 1978).

Table 6. Recommended soil fertility standards for northern red oak (Wilde 1958, Williams and Hanks 1976).

Element	Standard
Soil pH	5.0-6.0
Total N	12%
Available P_2O_5	78.46 kg/ha
Available K_2O	224.17 kg/ha
Cation exchange capacity	7.0 Meq/100 g
Exchangeable Ca	2.5 Meq/100 g
Exchangeable Mg	1.0 Meq/100 g

Adequate soil moisture in the fall is needed for good leaf retention into the late fall (Johnson 1981a). Retention of leaves into the fall can promote the translocation of carbohydrates and growth regulators to the root system. However, irrigation schedules should allow adequate time for hardening in the fall.

5.0 CONTAINER CULTURE

Red oak grown as bareroot nursery stock has a reputation for mediocre growth and field performance (Wendel 1980, Dixon et al. 1981a, McGee and Loftis 1986, Parker et al. 1986). Typically, bareroot seedlings grow slowly and are quickly overtopped when outplanted on high-quality sites. In bareroot stock, bud break precedes root growth, which may contribute to transplant shock and reduced photosynthetic area in planted seedlings (Struve and Joly 1992). Similarly, Dixon et al. (1981b) reported that delays in the onset of new root growth may have caused water and nutrient stresses that resulted in poor shoot growth, shoot dieback and mortality of field-planted bareroot black oak (*Quercus velutina* Lam.). In addition to slow root growth, the roots of field-grown oaks can be "highly suberized" and generally dysfunctional with respect to water absorbtion. Furthermore, both Johnson et al. (1984) and Dixon et al. (1981b) observed that new root growth was initiated mainly at the point of root pruning in bareroot stock, and that few laterals remained on the original taproot.

Red oak may flush four or more times per year when environmental factors are not limiting. Farmer (1975a) observed that when red oak is given adequate light, moisture and nutrients in greenhouse culture, it is capable of significantly greater growth than is usually seen in most nursery-grown 1-0 red oak. Therefore, one objective of container culture is to take full advantage of this potential for rapid juvenile growth. In container culture, soil moisture and nutrient regimes can be controlled and modified to enhance shoot and root growth beyond what can be attained under field conditions. Oaks raised in containers can develop a dense, fibrous root system with a tap root length equal to the container's depth. Lateral root development is enhanced by the "air pruning" of roots in bottomless containers (Johnson 1981a, 1989; Dirr and Heuser 1987). Thus, the intact root systems of container-grown seedlings have many root tips that serve as sites for new root regeneration. These desirable characteristics of container stock may reduce transplant shock and improve the outplanting performance of oak.

Container-grown oaks produce larger leaf areas and experience less shoot dieback than bareroot stock (Dixon 1979, Johnson et al. 1984, Struve and Joly 1992). Container stock also initiate root and shoot elongation sooner than bareroot stock. These advantages of container stock may explain, in part, why they outperform bareroot stock in clearcuts, for similar initial seedling sizes (Johnson 1984a, Zaczek et al. 1991, Zaczek et al. 1993). However, container stock underplanted in shelterwoods have not performed better than bareroot stock.

5.1 Container Stock Culture

In greenhouse culture, seedlings are usually grown under an extended photoperiod (16 to 18 hours), using sodium-vapor lamps to supplement natural light and over an extended growing season (e.g., February to September). Temperatures are usually maintained between 22 and 34°C. Farmer (1975a) found that the largest container-grown red oak were produced in full sun at 23°C when seedlings were well-watered and fertilized. Seedlings should be fertilized weekly using a balanced nutrient solution, complete with micronutrients (Farmer 1975a). The number of bud flushes, shoot growth, biomass and caliper for all seedlings increased significantly as additions of an 18-6-12 fertilizer increased from 0 to 6 grams/container (Hathaway and Whitcomb 1977). Fertilization of seedlings during growth periods increased significantly their biomass and survival following transplanting. Seedlings should be kept well watered to avoid even minor drought conditions. Nutrients can also be delivered to seedlings when they are watered. Tinus (1980) and Tinus and McDonald (1979) have provided detailed procedures for growing oak in containers.

Greenhouse-grown container stock should be allowed to harden off before fall planting or overwinter storage. This can be accomplished by gradually reverting to the natural photoperiod and allowing greenhouse temperatures to equilibrate with outside temperatures, or by moving stock outdoors to a shade-house in mid-summer, after the third shoot flush (Crow and Isebrands 1986). In the shade-house, seedlings should receive approximately 50 to 60% of full sunlight (Johnson 1984a). Red oak container stock can be overwintered in cold storage at temperatures of between 2 and 4°C (Johnson et al. 1984). They should be watered once per week while in cold storage to reduce water stress.

5.2 Container Type

Container size and shape can have a great influence on seedling shoot and root growth. Hanson et al. (1987) found that the number of flushes, number of leaves, shoot weight and lateral root biomass increased with increasing diameter of the container. Increasing container depth significantly increased tap root length but did not increase total root biomass. In fact, seedlings grown in deep containers exhibited consistently smaller mean leaf and stem weights than those grown in shallower containers of the same diameter. Apparently, deep containers allow seedlings to allocate more resources to root growth than to shoot growth. A surface area to depth of container ratio of 5.4:1 produced seedlings with the best combination of shoot and root growth (Hanson et al. 1987).

In conventional greenhouse culture, acorns are sown in deep containers (e.g., 500-mL), which are usually filled with a 1:1 mixture of peat moss and vermiculite. Johnson (1974) grew oak in containers ranging in volume from 164 to 500 mL and reported that these containers were capable of growing larger stock than other containerized systems. Increasing container volumes from 676 to 1,360 cm^3 while maintaining the surface area of all containers at 7 cm^2 did not significantly increase shoot height, root weight, or the caliper of red oak seedlings (Hathaway and Whitcomb 1977). Johnson (1981a) recommended using containers up to 750 mL in volume and 25 cm deep.

Poorly designed containers can also cause root deformation. Hathaway and Whitcomb (1977) grew red oak seedlings in bottomless milk cartons. They found that the right-angled corners of milk cartons reduced the amount of root girdling that commonly occurs in containers with round walls. When placed on wire benches, open-bottomed milk cartons produced red oak seedlings with air-pruned tap roots and a fibrous system with little spiral growth.

5.3 Mycorrhizae and Container Stock

Because containerized seedlings are frequently grown in sterile or soilless media, such as peat moss and vermiculite, silviculturists have attempted to introduce the symbiotic fungi normally present in forest soils into the containers. Marx (1979a,b) and Dixon et al. (1984) have found the genus *Quercus* to be an excellent host for the ectomycorrhizae *Theleophora terrestris* (Ehrh.) Fr. and *Pisolithus tinctorius* (Pers.) Coker and Couch.

Dixon et al. (1984) inoculated English oak, black oak and white oak with 11 different species of ectomycorrhizae. Of the mycorrhizal species tested, *P. tinctorius* 185, *T. terrestris* 223, and *Suillus luteus* (L.:Fr.) 224 consistently colonized each species of oak. In general, all seedlings inoculated with *P. tintorius* outgrew seedlings inoculated with other ectomycorrhizae, suggesting that fungal inoculations could be practical for container-grown oak.

In field trials conducted by Parker et al. (1986), container-grown black oak inoculated with *P. tinctorius* had significantly larger height increments and leaf areas than 1-0 bareroot stock after one growing season, even though the bareroot oak was twice as large as the container stock at the time of planting. Similarly, inoculated containerized seedlings had larger height growth increments than 2-0 bareroot stock during the first three growing seasons. Parker et al. (1986) suggested that the growth differences were primarily due to the more fibrous root systems of container-grown stock and only secondarily to the infection by ectomycorrhizae. The poorer performance of the bareroot stock was attributed to the damage done to root tips during lifting and planting, because root growth was minimal in planted bareroot seedlings.

Dixon et al. (1981b) cautioned that traditional nursery and greenhouse cultural practices may not be suited to the production of oak seedlings inoculated with mycorrhizal fungi. For example, watering black oak seedlings to container capacity everyday increased root dry mass but significantly decreased colonization by *P. tinctorius* ectomycorrhizae compared with plants watered on alternate days. Colonization by the fungi was also found to be negatively correlated with the concentration of supplied nutrients. Complete nutrient solutions applied at high concentrations (750 ppm NPK) produced seedlings with larger height, root dry mass and root collar diameter than those fertilized less. However, colonization by *P. tinctorius* was significantly lower in seedlings at the high fertilizer rate than for seedlings fertilized at medium (375 ppm NPK) and low (100 ppm NPK) nutrient concentrations.

Similar responses to fertilization treatments were also reported by Ruehle (1980) for container-grown red oak. Thus, fertilization and watering regimes are critical in promoting the colonization of oak roots by ectomycorrhizae.

6.0 DIRECT SEEDING

Direct seeding is a potentially viable method for regenerating oak. It is less expensive than planting nursery stock and is not as seasonally dependent as planting (Johnson and Krinard 1985, Steiner et al. 1990, Pope 1993). Direct-seeded oaks develop natural root systems on the site, thus eliminating the root injuries associated with planted bareroot stock. Direct seeding has particular advantages in regenerating oak on shallow-soiled sites, where planting large bareroot stock is difficult and expensive. When harvesting cannot be delayed until the next good acorn crop, direct seeding can be used to supplement advance reproduction.

Direct seeding is used widely to regenerate oak in the lower Mississippi River Valley (Kennedy 1993). Johnson and Krinard (1985, 1987) and Johnson (1984b) have successfully regenerated southern oaks by direct seeding. Oaks have also been successfully regenerated by direct seeding in the Lake States and Pennsylvania (Shirley 1937, Sholz 1964, Bowersox 1993, Zaczek et al. 1993). The germination rate may be as high as 85% and survival may be as good as other sources of oak reproduction (Shirley 1937, Stroempl 1990, Bowersox 1993). The height growth of direct-seeded red oak may equal that of 1-0 bareroot several years after planting in clearcuts (Bowersox 1993, Zaczek et al. 1993). Once established, direct-seeded oak exhibits the same slow growth characteristic of all oak reproduction. Regeneration success depends on the ability of oak to outgrow competing vegetation.

6.1 Predation of Acorns by Small Mammals

Although there have been occasional successes in regenerating oak by direct seeding, the practice has typically not been successful (Krajicek 1960, Sluder et al. 1961, Scholz 1964, Russell 1971, Mignery 1975, Marquis et al. 1976, Johnson 1981b, Zaczek et al. 1991). Consumption or destruction of acorns by small mammals is cited as the major cause of direct-seeding failures (Shirley 1937; Bramble and Sharp 1949; Krajicek 1955; Bonner 1965; McElwee 1970; Johnson 1981b, 1983; Johnson and Krinard 1985, 1987; Kerr 1986; Kelty 1988; Bowersox 1993). Mice, voles, chipmunks and squirrels damage acorns both before they germinate and during the early stages of seedling development (Nichols 1954, Pope 1993). Acorn consumption by small mammals often occurs within weeks following sowing (Smith 1993). Where populations of small mammals are dense, direct seeding has been unsuccessful (Shirley 1937, Bonner 1965). Sullivan and Sullivan (1982) reported that 85% or more of lodgepole pine (*Pinus contorta* Dougl.) seed is destroyed within three weeks when rodent densities exceed four animals per hectare. Successes in direct seeding of oak are often attributed to low population levels of small mammals (Shirley 1937, Marquis et al. 1976, Wendel 1979, Zaczek et al. 1993).

6.2 Control of Small Mammals

Efforts to reduce the amount of acorn predation by rodents have led to the development of a variety of control techniques. Poisoned baits, chemical repellents and scent-treated acorns have been unsuccessful in reducing acorn predation (Shirley 1937; Nichols 1954; Johnson and Krinard 1985, 1987; Pope 1993). Physically protecting acorns from rodents by covering seeds with wire mesh screens is one of the more effective means of reducing predation, but it is costly to administer (Shirley 1937, Stoeckler and Scholz 1956, Krajicek 1960, Sluder et al. 1961, Scholz 1964, Russell 1971). Plastic tree shelters provide adequate protection for red oak when they are installed immediately after sowing and are set below the soil surface (Figure 14) (Smith 1993). Unfortunately, most of these control measures are usually cost-prohibitive (Russell 1971, Johnson 1994a).

6.3 Timing of Sowing

The amount of acorn predation is also influenced by other activities associated with regeneration such as the timing of sowing, vegetation management and site preparation. It is not entirely certain whether it is better to sow red oak in the spring or fall. Those that recommend spring sowing attribute better germination to lower rodent populations in the spring and the reduced time that seed is available to rodents (Shirley 1937; Nichols 1954; Sullivan 1978, 1979b; Pope 1993).

Figure 14. *Plastic tree shelters have been used effectively to protect planted acorns from predation by small mammals.*

Fall sowing may be beneficial because:

- the germination rate is higher than in spring sowings,
- it eliminates the need for overwinter storage of seed,
- fall-sown seeds are planted when the availability of alternative foods is high,
- fall-sown seed germinates in the spring as soon as temperatures are warm enough, which is earlier than in most spring-sowing operations,
- germination of fall-sown seed is less likely to be affected by a dry spring than that of acorns planted in the late spring, and
- acorns sown in the fall are less attractive to rodents than spring-planted acorns.

However, others report that the time of year has practically no influence on the success of direct seeding provided the soils are not too dry or wet (Nichols 1954; Sluder 1964, 1965; Russell 1971; Sander 1982; Johnson and Krinard 1985, 1987; Jacobs and Wray 1992; Pope 1993; Timmons et al. 1993). For example, sowing in the summer has been used to regenerate southern red oaks in the United States (Johnson and Krinard 1987, Kennedy 1993). For white oaks, there is consensus that acorns should be sown immediately after fall collection because white oak lacks embryo dormancy and begins germination in the fall (Arend and Scholz 1969, Sander 1982, Johnson and Krinard 1985, Jacobs and Wray 1992, Kennedy 1993). Regardless of season, sowing seed during years of good to bumper acorn crops may reduce the amount of predation on planted seed (Timmons et al. 1993). Sowing an abundance of seed, such as occurs during a good acorn crop year, may also prove successful when predators are satiated.

6.4 Depth of Sowing

Broadcast sowing of acorns on forest sites or on open fields results in poor germination and regeneration failures, even when acorns are protected from rodents (Sluder et al. 1961, Sluder 1965, Sander 1982, Timmons et al. 1993). Seeds desiccate on the soil surface, which inhibits germination. A covering of litter or soil prevents acorn desiccation and is necessary for good germination (Korstian 1927, Barrett 1931, Sander 1982, Johnson and Krinard 1985, Pope 1993). Sowing depths of from 1 to 15 cm are suitable, but there is little advantage to sowing deeper than 10 cm (Johnson and Krinard 1985, 1987; Kennedy 1993; Pope 1993; Zaczek et al. 1993). If surface soil temperature and moisture conditions are expected to be a problem during the growing season, then acorns should be sown deeper (e.g., 5 to 10 cm) (Johnson and Krinard 1987). The depth of sowing has not consistently been linked to the amount of rodent predation, though acorns planted deeper than 5 cm may be less likely to be damaged (Russell 1971; Johnson 1981b; Johnson and Krinard 1985, 1987). Sowing depth and seed size may influence percentage germination and initial seedling growth (Johnson and Krinard 1985, Kennedy 1993). Sowing acorns 10 cm deep reduced germination rate and percentage compared with seed planted 2.5 cm deep (Johnson 1981b). First-year seedling heights were inversely related to sowing depth for a number of southern red oak species (Johnson and Krinard 1985). Most authors recommend sowing acorns between 2.5 and 5.0 cm deep unless rodents are a problem or soil moisture and temperature are concerns (Arend and Scholz 1969, Russell 1971, Marquis et al. 1976, Johnson 1981b, von Althen 1990, Jacobs and Wray 1992, Kennedy 1993, Pope 1993).

6.5 Seed Quality

It is important that only high-quality seed be used for direct seeding. Seed should be floated in water before sowing to ensure that only viable seed is planted. If sowing is done in the spring, seeds should be stratified. Acorns that germinate in cold storage can still be sown because they produce seedlings even if their radicles are broken (Bonner 1982). Johnson and Krinard (1987) suggested that a mixture of seeds from several parent trees should be sown to maximize the genetic diversity of oak reproduction, provided that all seed sources have good phenotypic traits.

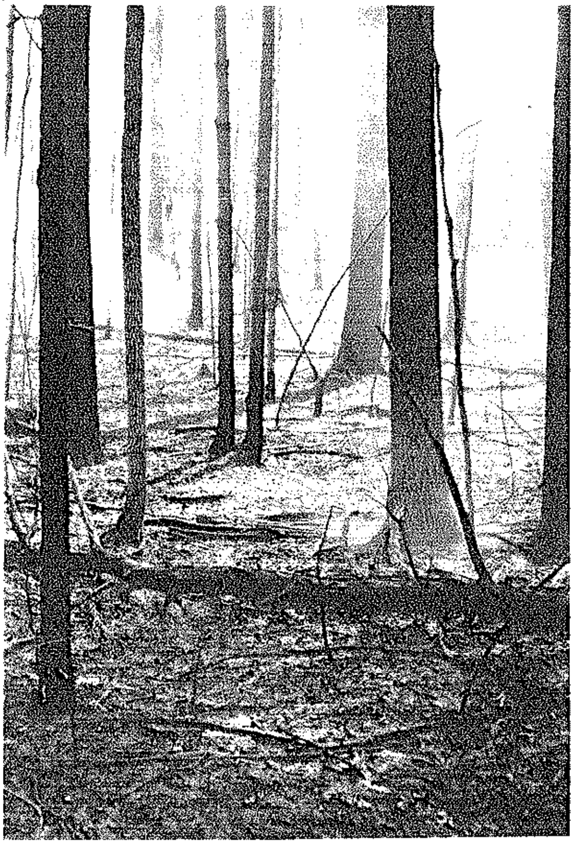
6.6 Site Preparation

Eliminating rodent habitat over large areas by removal or reduction of forest litter, logging slash and vegetation may reduce the amount of acorn loss to predation (Shirley 1937, Nichols 1954, Krajicek 1960). Prescribed burning and mechanical scarification not only aid in controlling competing vegetation but also influence the amount and distribution of rodent habitat (Figure 15). Single burns are effective in reducing habitat, especially the cover provided by fine fuels (Shirley 1937, Russell 1971, Sander 1982). Similarly, heavy mechanical site preparation that removes most of the logging debris in forest openings may reduce predation of acorns to less than 5% (Johnson 1981b). Without site preparation, direct-seeded acorns can be removed by herbivores within one week. In other cases, site preparation by burning, disking or plowing old fields and cutover sites failed to improve the establishment of direct-seeded oaks (Mignery 1962, Crozier and Merritt 1964, Russell 1971).

6.7 Size of Opening

The size of forest opening and amount of rodent habitat influence the amount of acorn predation. Litter removal around the seed spot does not by itself reduce the loss of acorns to mice (Nichols 1954). Direct seeding under closed canopies or in single-tree gaps results in substantial rodent damage to acorns (Johnson and Krinard 1985, 1987;

Figure 15. *Reduction of small mammal habitat may improve the success of oak regeneration by direct seeding. Leaf litter, woody debris on the forest floor and ground vegetation provide ideal habitat for small mammals (lower right). A spring prescribed burn in an oak stand in the Dufferin County Forest was effective in eliminating the litter layer, reducing the amount of fine woody fuels and decreasing the amount of ground vegetation (upper right).*



After spring burn.

Unburned stand.

Jacobs and Wray 1992; Pope 1993). Johnson (1981b) reported that rodents removed all acorns planted in undisturbed forests within one week and damaged 75% of the acorns sown in 12- x 27-m cleared strips. Rodents are less likely to move into large openings that do not provide sufficient security cover (Johnson 1981b). Sowing in large openings has been recommended as a way to reduce rodent predation (Johnson 1983, Kerr 1986, Sims 1986, Johnson and Krinard 1987, Jacobs and Wray 1992). Johnson and Krinard (1987) found that rectangular openings of 76 x 76 m had considerably less rodent damage to planted acorns than smaller openings. They recommended that site prepared forest openings be at least 30 m on a side. Their results are supported by Russell (1971), who observed that the majority of acorn damage by both mice and squirrels occurred in forest openings within 30 m from an adjacent hardwood forest. In general, as opening size increases, rodent predation of acorns decreases, provided that habitat cover has been reduced. Fewer than 5% of sown acorns were damaged by rodents on site prepared forest openings 1 ha in size (Johnson 1981b, Johnson and Krinard 1985, Pope 1993). However, the growth of competing vegetation is favored in larger forest openings and slow-growing oak reproduction is less likely to be competitive without vegetation control (Johnson 1984b, Jacobs and Wray 1992).

6.8 Density of Sowing

The required density of sowing depends on the desired oak stocking, the germinative capacity of the acorns and the amount of acorn predation. The germinative capacity of any seedlot should be determined before calculating a seeding rate. However, professional experience is required when fall-sowing red oak because germination tests cannot be performed in the fall for red oak species. Various recommendations have been offered for determining sowing rates for oaks. Both Kennedy (1993) and Johnson and Krinard (1987) suggested that 35% germination is a typical rate for red oaks and report that 2500 to 3700 seeds per hectare can be expected to produce 750 to 1200 one-year-old seedlings per hectare. These sowing rates could produce from 370 to 925 free-to-grow oaks per hectare in 10 years (Pope 1993). Jacobs and Wray (1992) recommended sowing at least twice as many spots as trees wanted and that three to four seeds should be planted at each spot. Where rodent activity is high and litter is removed, 3.7 acorns should be planted to produce one seedling (Nichols 1954). However, there may be no upper limit to sowing density if the strategy is to provide predators with more acorns than they can eat. Nature satiates acorn predators when oaks produce bumper seed crops. Sork et al. (1993) hypothesized that the periodic production of large seed crops by species such as red oak may represent an evolutionary response to cope with intense seed predation.

6.9 Diversionary Foods

Bonner (1965) and Bowersox (1993) have suggested that animal predation of direct-seeded acorns will be low if alternative food supplies are adequate. Animal predation of direct-seeded acorns may be especially intense in years of low natural acorn production or on non-oak sites that lack a natural acorn supply. Providing predators with alternative food sources has been successful in reducing losses of direct-seeded western conifers. Diversionary foods such as sunflower seeds and oat kernels have been effective in reducing conifer seed predation by deer mice (Sullivan 1979a; Sullivan and Sullivan 1982, 1984). However, recommendations for using diversionary foods to assist the regeneration of eastern hardwoods have yet to be developed.

7.0 SUMMARY

Artificial regeneration of oak by planting or direct seeding can be used to supplement natural oak reproduction or to reintroduce oak on sites where it once grew. Regeneration by artificial methods begins with the collection of mature, sound quality seed of known parentage and provenance. There is much genetic variability between individual red oak trees and stands of oak. Selection of trees with good phenotypic traits is an important first step. Sowing genetically similar seedlots from superior trees results in the production of uniform, high-quality stock. Local seed sources are preferable.

Seed quality and size have a strong influence on many of the morphological and physiological characteristics of red oak. During seed collection, acorns should be inspected for soundness, maturity and quality using the cut test and by visual inspection of a sample of acorns from each seed source. Flotation of acorns in water is a good way of separating quality seed from those that are damaged or immature. Acorn quality and viability is maintained before fall sowing or over-winter storage by keeping them cool and moist. Loss of seed moisture content causes reductions in seed quality and germinative capacity. Seed moisture content should be checked before sowing, stratification or during long-term storage. When seed moisture content falls below 25% for extended periods, seed viability is reduced.

Red oak sown in the fall undergoes stratification naturally over the winter. Red oak placed in cold storage over-winter is stratified after 30 to 90 days. It is important that the seed moisture content be maintained above 30% and that the seed is well-aerated. Polyethylene bags of 4- to 10-mil thickness are good for long-term storage of acorns.

Seed testing for quality, maturity, moisture content, germinative capacity and germination rate is used to determine the suitability of a seedlot for collecting, sowing and storing. These tests are used to monitor and maintain favorable acorn condition, especially during long-term storage. Sowing or storing only high-quality seed minimizes regeneration costs, improves control over nursery seedbed densities and increases the chances of establishing vigorous seedlings.

Nursery cultural practices influence the physical characteristics of planting stock, as well as their field performance. The quality of Ontario produced red oak stock is highly variable and generally below the standards recommended by many researchers. Stock quality standards in relation to field performance have been developed for red oak. It is recommended that 2-0 red oak bareroot stock have five or more permanent first-order lateral roots, stem diameters (2 cm above the root collar) larger than 8 mm and shoot lengths that exceed 50 cm.

Seedbed density has a strong influence on stock quality and the uniformity of stock characteristics. Growing red oak at uniform spacings and lower seedbed densities produces a high percentage of plantable seedlings and few culls. Recommended seedbed densities for red oak range from 32 to 86 seedlings/m^2.

In general, undercut red oak perform better after outplanting than uncut seedlings. It is recommended that red oak stock be undercut during the first year and that stock be allowed a second year in the nursery to develop sufficient height and diameter before being outplanted. Undercutting should be done at depths between 13 and 15 cm.

Red oak stock should be lifted in the spring to maximize seedling vigor and physiological condition. At lifting time, roots should be pruned to a vertical length of 20 to 25 cm and a horizontal length of 15 cm. If stock is lifted in the fall, it should be stored over-winter in a cooler rather than outdoors in heel-in beds. Seedlings properly stored over-winter experience less shoot dieback

and are in better physiological condition than those stored in heel-in beds. Stock overwintered in heel-in beds are also subject to increased levels of infection by root rotting fungi.

Reports on the effect of shoot clipping on survival and growth of red oak vary considerably. However, it is recommended that shoots be clipped at about 20 cm above the root collar close to the time of planting, especially for larger stock.

The benefits of container-grown red oak versus bareroot have been demonstrated in many situations. Container-grown stock have a more dense, fibrous root system, experience less shoot dieback, produce larger leaf areas and initiate root and shoot growth earlier than bareroot stock. However, the cost of container production and outplanting is currently prohibitive.

Direct seeding is a potentially viable and economical means of regenerating red oak. However, acorn predation by small mammals is a major obstacle to successful seedling establishment. Physical protection of acorns using tree shelters or wire-mesh screens has been successful but is operationally expensive. High quality acorns can be sown in the fall or spring and should be planted about 2.5 to 5.0 cm deep. Silvicultural practices that reduce small mammal habitat (e.g., prescribed burning or mechanical scarification) may enhance seedling establishment. Sowing acorns in large openings where small mammal habitat has been reduced may decrease the amount of acorns lost to predators. Vegetation competition may need to be controlled in larger openings. Sowing an abundance of acorns, planting seed in years of good to bumper acorn crops or supplying diversionary foods (e.g., sunflower seeds) during seedling establishment may be used to increase regeneration success by direct seeding.

Research on nursery practices for bareroot and container red oak culture has provided us with specific guidelines for the production of quality stock. Stock quality standards have been developed. Production of red oak seedlings that meet or exceed these standards will increase the probability of successful oak regeneration. Guidelines for regenerating oak by direct seeding are more speculative now, but we can begin formulating regeneration prescriptions that are more likely to succeed by using combinations of techniques that have worked in other areas.

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