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Impact of Storage on Viability of White Spruce Seed

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Abstract

Samples of seed of white spruce (*Picea glauca* [Moench] Voss) from 36 individual trees, collected in 1974 from 5 provenances in Ontario, Canada, were placed in frozen storage at -20 ˚C (-4 ˚F) in 1977 and in storage at 4 ˚C (39 ˚F) in 1982. Seed was removed from both storage temperatures and tested in 2002 and 2005. Seed moisture content increased on average, whereas average germination remained the same or declined slightly after storage at -20 ˚C (-4 ˚F) for 25 and 28 yr. For the same seedlots stored at 4 ˚C (39 ˚F) for 20 and 23 yr, seed moisture content also increased on average, whereas mean germination declined drastically. Seed moisture content exceeding 8.5 percent negatively impacted germination of seed stored at both temperatures. Seed stored at -20 ˚C (-4 ˚F) germinated faster than seed stored at 4 ˚C (39 ˚F). These results demonstrate the long-term storage potential of white spruce seed stored at -20 ˚C (-4 ˚F).

Introduction

Storage of tree seed is advantageous for reforestation programs, research, and genetic conservation. Maintaining the initial genetic and physiological quality of seed is one objective of storage (Wang and others 1993).

Several studies have shown that long-term storage of tree seed is possible. Simpson and others (2004), examining seed storage for 15 tree species, found that storage ability varied among species and suggested that seed of a number of species, including white spruce (*Picea glauca* [Moench] Voss.), could store well for 100 yr. Successful long-term storage also depends on storage conditions and treatment and quality of the seed (Wang 1976).

The major factors affecting seed longevity and viability in storage are storage temperature and moisture content (Bewley and Black 1994). Hansen and others (2005) found that germination of white spruce seed stored for 23 yr at -18 ˚C (0 ˚F) declined from 92 to 86 percent. Walters and others (2005) quantified germination data from seed of 276 agricultural and other plant species stored for 16 to 81 yr. They found that some species tended to survive longer than others during storage at both 5˚ (41 ˚F) and -18 ˚C (0 ˚F). The benefit of low-temperature storage at -18 ˚C (0 ˚F) on seed longevity was progressively lost if seed was first stored at 5 ˚C (41 ˚F) (Walters and others 2004). Wang and others (1993) reported that subfreezing temperatures to -20 ˚C (-4 ˚F) are considered better than above-freezing temperatures for long-term storage, provided the seed moisture content is less than 10 percent. Under these conditions, physiological activity is minimal (Leadem 1996).

Results are presented here from a white spruce seed storage experiment set up over 25 yr ago, using seed collected from individual trees from five provenances and stored at 4 ˚C (39 ˚F) and -20 ˚C (-4 ˚F).

Methods

In 1974, staff of the Tree Breeding Unit at the Petawawa Forest Experiment Station (now Petawawa Research Forest) collected white spruce cones from five locations in Ontario for a series of provenance trials. Samples were taken at Antrim (45˚19'; 76˚11'), Bancroft (45˚06'; 78˚58'), Petawawa (46˚00'; 77˚26'), Renfrew (45˚28'; 76˚44'), and Whitney (45˚32'; 78˚27'). Cones were collected 27 August–3 September from 10 to 47 individual trees spaced 20–100 m (65–325 ft) apart at each location. Seed was extracted and cleaned on an individual-tree basis during the autumn, tested for moisture content and germination, and stored in glass jars with threaded lids at 2 ˚C (35 ˚F). [Threaded lids with rubber seals enhance the hermetic qualities of a container best (Manager and others 2003).]

In February 1977, 10-g (0.36-oz) samples from 36 collections were set aside for germplasm preservation and evaluation of the storage ability of white spruce seed. Each sample was subdivided into four samples of 2.5 g (0.09 oz) each and placed into small, heat-sealed 5-mil thick poly bags;

the four subsamples were stapled together such that the staple did not penetrate the portion of the packets containing the seed. The packets of seed were placed in 1 L (1.06 qt) mason jars with a screw cap and stored at -20 ˚C (-4 ˚F). In 1982, seed samples from the original collections were prepared for storage at 4 ˚C (39 ˚F). Seed was placed in 5-ml (0.17-oz) vials with two vials per seedlot, and the two vials were placed in a small poly bag that was heat sealed. All bags from one provenance were placed into a larger poly bag that was also heat sealed.

Seedlots initially tested for moisture content and germination in late 1974 or early 1975 were selected for evaluation of seed storage ability. In 2002, 1 sample from each of 25 seedlots from the Whitney provenance was removed from each storage temperature and tested for moisture content and germination. In 2005, samples from the 4 other provenances (a total of 11) were evaluated to determine whether the trends found with the Whitney provenance were consistent.

Seed moisture content was determined by placing approximately 1 g (0.036 oz) of seed into each of two aluminum containers. The seeds were then dried for 17±1 h in a force-draft oven at 103±2 ˚C (217±4 ˚F), and moisture content was calculated on a fresh-weight basis [ISTA (International Seed Testing Association) 2006].

For the germination tests, seed was placed on moistened Versa Pak™ (Kimberly-Clark, Neenah, WI) in Petawawa germination boxes with a vacuum plate. Four replicates of 50 seeds were placed in each box. The boxes were moist-chilled for 21 d in a cooler maintained at 3 ˚C (37 ˚F). After 21 d, the boxes were placed in a Conviron G30 germinator at 8 h light at 30 ˚C (84 ˚F), followed by 16 h darkness at 20 ˚C (78 ˚F), with a constant relative humidity of 85 percent. Germinants were monitored at 7 d and every 3–4 d thereafter until day 21. Seed was considered germinated when cotyledons, hypocotyl, and a developing radicle had appeared.

Data were analyzed with SAS (SAS Institute, Inc., Cary, NC). Before analyses of variance, arcsine transformation was applied to the percentages.

Results

Seed moisture content and germination showed the same trends for the stored seed from all five provenances. Seed moisture content increased significantly from when the seed was initially tested to when it was removed from storage (table 1). The increase was less, however, for the seed stored at -20 ˚C (-4 ˚F).

Germination of seed stored at -20 ˚C (-4 ˚F) was unchanged from its original value for seed stored for 25 yr and declined only 1.2 percentage points in seed stored for 28 yr (table 2). Germination of seed stored at 4 ˚C (39 ˚F) for 20 and 23 yr, however, declined drastically. Germination of seed stored at -20 ˚C (-4 ˚F) varied less than of seed stored at 4 ˚C (39 ˚F), as indicated by the standard errors (SE).

Germination declined sharply for seed stored at 4 ˚C (39 ˚F) when seed moisture content exceeded 8.5 percent (table 3). Germination was also substantially lower for seed stored at 4 ˚C (39 ˚F) with moisture content between 4.5 and 6.9 percent than for seed stored at -20 ˚C (-4 ˚F). Indeed, with the exception of two seedlots, germination of seed stored at 4 ˚C (39 ˚F) was always lower, regardless of seed moisture content. Even in the case of four seedlots with similar moisture contents at both storage temperatures [6.0 percent at 4 ˚C (39 ˚F) and 6.2 percent at -20 ˚C (-4 ˚F)], the seed stored at -20 ˚C (-4 ˚F) had higher mean germination. These findings illustrate the impact of storage temperature on seed longevity.

Table 1. Comparison of seed moisture content of 25 white spruce seedlots from Whitney provenance with that of 11 seedlots from 4 other provenances after collection and after storage at -20 ˚C (-4 ˚F) and 4 ˚C (39 ˚F).

	Whitney[1]			Other provenances[1]		
Storage condition	**Mean**	**SE**	**Range**	**Mean**	**SE**	**Range**
Initial	4.6a	0.08	3.6–5.3	4.2a	0.13	3.5–5.0
– 20 ˚C (4 ˚F)	5.8b [2]	0.11	4.9–6.9	6.4b [3]	0.23	5.5–8.5
4 ˚C (39 ˚F)	7.5c [4]	0.34	5.6–10.0	8.2c [5]	0.45	5.2–9.5

[1] Within a provenance or provenance group, means followed by different letters differ significantly at p=0.05 by Duncan's test. SE=standard error.

[2] Seed was stored for 25 yr.

[3] Seed was stored for 28 yr.

[4] Seed was stored for 20 yr.

[5] Seed was stored for 23 yr.

Table 2. Comparison of percent germination of 25 white spruce seedlots from Whitney provenance with that of 11 seedlots from 4 other provenances after collection and after storage at 4 ˚C (39 ˚F) and -20 ˚C (-4 ˚F).

	Whitney			Other provenances		
Storage conditions	**Mean[1]**	**SE**	**Range**	**Mean[1]**	**SE**	**Range**
Initial	95.8a	0.75	83.8–99.2	91.4a	3.34	64.2–99.5
– 20 ˚C (4 ˚F)	95.8a [2]	0.71	84.5–99.5	90.2a [3]	2.46	71.0–98.5
4 ˚C (39 ˚F)	33.2b [4]	6.23	0.0–98.5	5.1b [5]	3.50	0.0–38.5

[1] Within a provenance or provenance group, means followed by different letters differ significantly at p=0.05 by Duncan's test.

[2] Seed was stored for 25 yr.

[3] Seed was stored for 28 yr.

[4] Seed was stored for 20 yr.

[5] Seed was stored for 23 yr.

Table 3. Germination (percent) by seed moisture content (MC) class for 36 white spruce seedlots stored at 4 ˚C (39 ˚F) or -20 ˚C (-4 ˚F).

MC class	**4 ˚C (39 ˚F)**			**– 20 ˚C (– 4 ˚F)**		
(percent)	**Mean**	**Range**	**Seedlots (no.)**	**Mean**	**Range**	**Seedlots (no.)**
4.5–4.9				98	—	1
5.0–5.4	25	10–39	2	95	90–100	5
5.5–5.9	37	7–68	7	95	84–99	12
6.0–6.4	57	12–88	5	94	83–100	12
6.5–6.9	6	—	1	95	92–98	5
7.0–7.4	—	—	—	—	—	—
7.5–7.9	—	—	—	—	—	—
8.0–8.4	98	97–99	2	—	—	—
8.5–8.9	11	0–34	7	71	—	1
9.0–9.4	3	0–12	6	—	—	—
9.5–9.9	1	0–3	5	—	—	—
10.0–10.4	0	—	1	—	—	—

Storage conditions also impacted germination vigor. Seed stored at 4 ˚C (39 ˚F) germinated later and more slowly than seed stored at -20 ˚C (-4 ˚F) (figure 1). Germination was complete by day 14 for seed stored at -20 ˚C (-4 ˚F), but continued up to day 21 for seed stored at 4 ˚C (39 ˚F). At day 21, seed that had not completed germination was counted and classified as being of low vigor. Seed stored at -20 ˚C (-4 ˚F) exhibited 0.9 percent low vigor germination, but this value almost doubled to 1.7 percent for seed stored at 4 ˚C (39 ˚F).

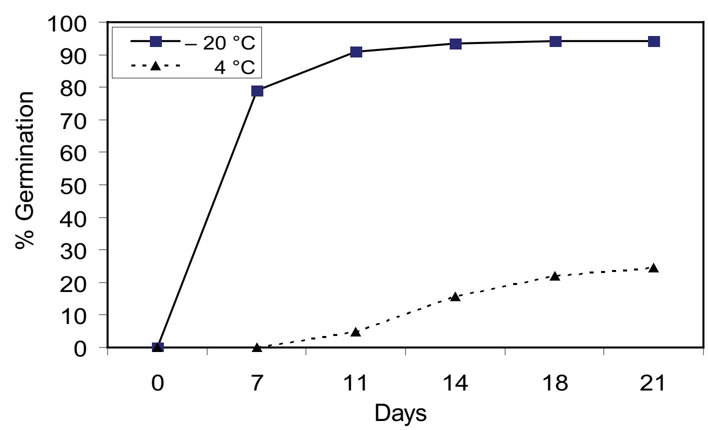

Figure 1. Germination speed of white spruce seed stored at 4 ˚C (39 ˚F) and -20 ˚C (-4 ˚F).

Discussion

The cone crop on white spruce in Ontario was heavy in 1974, as substantiated by the large number of accessions in the National Tree Seed Centre's database. This implies that the genetic and physiological quality of the seed crop that year was high as a result of presumed abundant pollen production and trees diverting a significant proportion of their resources to seed production. These factors should positively impact storage ability of seed collected that year. Willan (1985) stated that, in a good crop year, seed collected from trees with high production is likely to have the best longevity in storage. Caron and others (1993), however, reported that seed maturity at collection time varied between heavy and light crop years for white spruce. This points out that seed quality varies from year to year, and assessing seed quality before committing seed to storage is important.

Seed moisture content was higher after storage than shortly after seed processing. It is unlikely that the seed acquired moisture while in storage because of the manner in which it was packaged. More likely, the seed acquired moisture before storage because of improper seed handling. The seed was repeatedly taken from and returned to storage as seed was provided to cooperators to establish provenance trials. Possibly it acquired moisture from the air if seed containers were not allowed to equilibrate to room temperature before they were opened, or the seed lots were handled in high ambient relative humidity. The seed stored at 4 ˚C (39 ˚F), in particular, may have had a higher moisture content before being placed in long-term storage, because the samples were prepared after all seed requests from cooperators establishing provenance trials had been satisfied.

Seed moisture content has been considered a critical factor for the life of seed in storage (Holmes and Buszewicz 1958; Bewley and Black 1994; Hong and Ellis 2002). Storage temperature also interacts with seed moisture content. Barton (1961) pointed out that the higher the storage temperature, the faster the rate of seed deterioration for seed with a given moisture content; at a lower storage temperature, there is greater tolerance for higher moisture content. A storage temperature above freezing is not sufficient to maintain viability of seed with low moisture content because the seed continues to metabolize and deplete its energy reserves, resulting in death. When seed tissues are frozen, metabolic activity is substantially decreased, and the reserves stored in the megagametophyte remain intact.

In this study, moisture content of the two groups of seed stored at 4 ˚C (39 ˚F) increased on average, with a corresponding decline in mean germination. Although the moisture content of seed of the same two groups stored at -20 ˚C (-4 ˚F) also increased, germination remained unchanged or declined only slightly. Seed with a moisture content above 8.5 percent had consistently lower germination. Daigle and Simpson (2003) reported that seed moisture content above 9 percent had an increasingly negative impact on germination of white spruce seed stored at -20 ˚C (-4 ˚F). A moisture content of 5±1 percent is recommended for long-term storage for gene conservation (FAO/IPGRI 1994).

Vigor of germinating seed is a useful trait to evaluate impact of storage. As seed ages, vigor declines, and eventually the seed dies. Total germination is also important, but does not take vigor into account. At the completion of the germination test, the number of low-vigor germinants was twice as high for seed stored at 4 ˚C (39 ˚F) as for seed stored at -20 ˚C (-4 ˚F). The impact of storage temperature on seed vigor was also evident in the germination speed.

Conclusions

Results presented in this paper illustrate the potential long-term storage ability of white spruce seed, which is advantageous when storing seed for *ex situ* gene conservation.

1. Germination of seed stored for 25 and 28 yr at -20 ˚C (-4 ˚F) exhibited little or no change.

2. Germination of seed stored for 20 and 23 yr at 4 ˚C (39 ˚F) declined by up to 82 percent.

3. Germination of seed stored at -20 ˚C (-4 ˚F) started sooner, occurred faster, and reached its maximum sooner.

4. Seed moisture content greater than 8.5 percent negatively impacted germination, particularly in seed stored at 4 ˚C (39 ˚F).

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The Making of a Cooperative Forestry Program

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Abstract

Forestry cooperatives have the objective of accomplishing a goal by group, rather than by individual effort. Ingredients for a successful cooperative include enthusiastic leadership and committed clientele. For the Cooperative Programs at North Carolina State University, all cooperators are treated equitably, regardless of size, age, or state of knowledge, to operate at a defined threshold level of activity, and all are required to share research results and plant materials with other cooperators. Research results are made available to the public with minimal delay. Continuing education is an essential part of any successful forestry cooperative.

Introduction

Forest tree improvement programs are complicated by the long time required for trees to reach sexual maturity; the long reproductive cycle, which extends through two years for most conifers; and the long time required for the resultant progeny to reach financial maturity. In addition, the logistics of consummating controlled crosses and obtaining seed and scion material from mature trees that range to 50 meters tall are restrictive. The time, effort, and finances required to conduct such a program on a scale to produce improved plant material for operational use while maintaining a broad genetic base for future cycles of breeding are generally prohibitive for all but a few public organizations. Even those organizations lack the alacrity to accomplish both short- and long-run objectives. The alternative is to accomplish the job by group effort, rather than by individual effort.

Note from the Managing Editor: This paper was presented almost three decades ago with the precise purpose of making it clear how forestry benefited from cooperatives. It is a remarkable reminder of how far we have come as a result of forestry cooperatives with some good thoughts on how cooperatives can keep forestry strong in the future. Reprinted with permission of the author, who is now retired.

The group effort for genetic improvement of forest trees was envisioned by Dr. Bruce J. Zobel in 1951. Employed as a silviculturist by the Texas Forest Service, Dr. Zobel organized a coalition of southern forest industries to fund and conduct the necessary research for formation of an operational tree improvement program. Reliance on private industry to accomplish the job was as surprising then to the South as it is now to other regions within and outside the United States. Antagonists were convinced that public agencies were the only organizations suited to conduct long-range research, and they were equally convinced that the private industry was too fickle for long-range commitments. How could private organizations of a strongly competitive commodity group organize to accomplish a common goal? The structure and accomplishments of the North Carolina State University-Industry Cooperative Tree Improvement Program, with frequent reference to other forestry cooperatives, are recounted to answer that question.

Cooperative Defined

A cooperative is defined as a means of working together to achieve a common goal. That loose definition has allowed extension of the principle to mean involvement from the least to the greatest degree. Farmer alliances are examples of the lesser degree of cooperative involvement. For a fee, which is usually exacted from the selling price of the commodity, the farmer can deliver his tobacco, corn, or cattle to the cooperative, which assumes all responsibility for selling to the processor. Better prices and greater assurance of selling are the rewards of the cooperative effort, in which the farmer usually has no investment. He is involved only to the degree that he commits his crop to the venture.

The end opposite farm alliances on the spectrum of cooperatives is total involvement of all members in all activities. Added stipulations are that all members be treated equitably, regardless of size, state of knowledge, or longevity, and each organization be required to perform at a threshold level. Anyone failing to meet these standards would be declined admission or purged. It is the latter type of organization to which we will address our attention.

Cooperative Perceived

A forestry cooperative works best when the need for the joint effort is perceived by its potential members. The succeeding step is presentation of the proposal to a number of public agencies or foundations to determine who has superior capabilities for administering the project. Being involved in the decision to house the project within a specific agency induces harmony among the cooperators.

Successful forestry cooperatives also exist as a result of an enterprising person or group of people convincing the clientele of the value of a combined effort. In the beginning such cooperatives almost always attract fewer cooperators than anticipated. The result is to increase the fee structure of member organizations to form an acceptable operating budget or to operate on a reduced budget. Neither option is attractive; member organizations express lack of confidence in the first instance, and results are slowed in the second instance. The only way such a program can succeed is by accomplishment. A degree of respectability is gained when results are obtained; failure results when they go begging.

A variant of the joint effort perceived by potential members is additional funding of a project already in existence. Support by a couple of organizations that first recognize the value of the research often serves as a catalyst for contributions by other organizations until a full-fledged cooperative is formed. The Herbicide Cooperative at Auburn University, Alabama, is an example of such a success story.

Cooperative Ingredients

Successful forestry cooperatives need not be formed to the same mould. Greatest differences are in the authority vested in the directors. Some directors are given broad control, whereas others have to operate within the confines of committee action. I espouse the broad control method because it has been used successfully by the Tree Improvement, Hardwood Research, Forest Fertilization, Forest Equipment/ Systems, and Tissue Culture Cooperatives at North Carolina State University. The method presupposes that the director is the expert on the subject and that his judgment is valued over that of a committee, each member of which knows relatively less about the subject than the director.

Justification. Major reasons for support of cooperative programs by forest industry in the South are diversity of land ownership and time, cost and effort of conducting long-range research. Most organizations supportive of cooperatives own or control from 80,000 to 2,000,000 ha of land. Within an ownership, the land extends across several geographic provinces, many states, and a multitude of site productive classes. The diversity prohibits the intensity of research needed for each classification, even for those organizations with a large support staff. The philosophy is that a coordinated effort by a group of organizations can accomplish more in a given time at a cheaper cost than can each of the organizations working separately.

Coordinator. In order to render impartial decisions, it is imperative that the coordination of a cooperative forestry program be vested in an institution distinct from that of its members. Forestry schools within major universities have commonly filled these roles in the South, although the U.S. Forest Service has coordinated cooperative programs in pollen management, lightwood production, and introduction of *Eucalyptus* (table 1).

Requirement. The North Carolina State Tree Improvement Program operates without a contract of any type. Initial verbal agreement was to support the program for five years, after which time the cooperators were free to withdraw if unsatisfied with results. The director was also given authority to terminate membership if a cooperator did not perform to a threshold level. Some cooperatives also discourage renewed membership of organizations who terminate participation at periodic intervals. Nothing is more damaging to a cooperative program than a member who benefits at the expense of other cooperators. An unqualified stand against such practices has resulted in the North Carolina State Tree Improvement Program's growing from 10 members in 1956 to 30 members in 1979 without a single casualty.

One of the greatest benefits of a tree improvement cooperative is the amassing of a genetic base that would be almost prohibitive for any one organization to amass. Free exchange of the plant material then becomes imperative if the cooperators are to benefit from the best genetic material. It is not common in the Tree Improvement Program for a clone of outstanding genotype to be found in the seed orchards of a half-dozen cooperators, and progeny from an outstanding clone in Virginia are likely to be under test on lands of a separate cooperator in Mississippi.

Another major requirement of the Tree Improvement program is that all information obtained through the auspices of that program will be made available to all other cooperators without delay and to the public as soon as the

Table 1. Cooperative forestry programs in the South, by state and institution.

State	Institution	Cooperative type
Virginia	Virginia Polytechnic Institute and State University	Biometrics
North Carolina	North Carolina State University	Tree improvement
		Hardwood silviculture
		Forest fertilization
		Forest equipment/systems
		Tissue culture
Georgia	University of Georgia	Biometrics
Florida	University of Florida	Tree improvement
		Forest fertilization
Alabama	Auburn University	Herbicide evaluation
Mississippi-Louisiana	Mississippi State University and Louisiana State University	Harvesting systems
Texas	Texas A&M University	Tree improvement
		Hardwood silviculture
	U.S. Forest Service (Southeastern Forest Experiment Station)	Pollen management
		Lightwood induction
		Eucalyptus introduction

information can be disseminated in oral or narrative form. In the 23 years the Cooperative has been in existence, the rule has rarely been challenged. Most cooperatives follow the principle of the Tree Improvement Program in disseminating results. However, some programs delay dissemination of the information for a time not to exceed two years, to allow member organizations to profit from the results.

It is a requirement of the Tree Improvement Program that all trees grafted into seed orchards will have been graded by the program staff. The other stipulation is that the experimental design of progeny tests and other region-wide field trials be common among all cooperators. The former requirement assures a common base for genetic improvement of the southern pines, and the latter one adds efficiency to data collection, analysis, and interpretation. Most other cooperative organizations of a similar nature have similar requirements.

Although the absolute requirements of the Tree Improvement Program are few, advice and recommendations are freely given on topics ranging from orchard establishment to deployment of genetically improved plant material. The technical representative is free to reject our counsel, but he and his superiors are reminded that we assume no responsibility for failure if our advice is rejected. We are quick to admit failure when we have given a wrong recommendation, but are just as quick to disclaim responsibility when the fault lies with the cooperator.

Qualification. Cooperative forestry programs require long-term commitments of money and manpower. The amount of money contributed to the coordinating unit is small in comparison to the expense of establishing and maintaining research and operational trials on cooperator lands. The cost to a single cooperator in tree selection, orchard establishment, progeny testing, and collection and deployment of plant material in the Tree Improvement Program is up to 40 times that allocated to program coordination. That consideration has caused us to recommend against membership of any organizations controlling less than about 80,000 ha of land. Such organizations are advised to support the programs of their respective state forest services, from which genetically improved plant material can be obtained.

The Tree Improvement Program was formed with the sole support of forest industry. That policy was subsequently changed to allow participation by state forest services. The Forest Service of Virginia, North Carolina, and South Carolina are now among the 30 members of that program in which all participants are treated equally. The forest services of these and other southern states, as well as the U.S. Forest Service, also support one or another of the various cooperatives listed in table 1.

Trade associations and commercial enterprises without a land base, which would benefit directly from cooperative membership, are discouraged from joining except as a patron. Membership is generally decided on the recommendation of the director, with final approval being the responsibility of the advisory committee.

Administration. With the implicit approval of the cooperators, a director is appointed by the coordination organization, such as the university where the cooperative is housed. The director is responsible for composing a staff of the quality and quantity needed to conduct the business of the cooperative.

Contact between the director and the cooperator is made at two levels for most cooperative programs. The administrative contact is made through the advisory committee, which is composed of one administrator from each cooperator. The administrator has sufficient authority to make policy decisions regarding cooperative matters. Contact is maintained with the advisory representative throughout the year, and an advisory committee meeting is held annually, at which time a report is made to the director on accomplishments and plans and on financial status of the cooperative. The advisory committee interacts with the director on these matters.

The second level of contact by the director and the cooperator is with the technical representative. The technical representative, generally a graduate forester with a baccalaureate or master's degree, is responsible for cooperative activities of the cooperator. Although an employee of the cooperator, his duties are largely influenced by directives of the cooperative. Annual meetings are commonly hosted by the cooperators on a rotating basis to allow the technical representative to show his accomplishments and to see the accomplishments of his peers. Superiors of the technical representatives are excluded from these meetings to allow latitude in discussion.

Finances. Financing of a cooperative program is usually jointly funded by the cooperators and the coordinating unit. The cooperatives at North Carolina State University enjoy the use of the capital plant, inclusive of facilities without the cost of overhead. The salary for the director, or an equivalent amount of money, and costs for associated goods and services are borne by the university. Monies collected from the cooperators on a scheduled basis are used for salaries of the support staff and graduate students and for goods and supplies for day-to-day operations. Cooperator fees are self-imposed at the annual meeting for the following year, based on the budgetary process.

All organizations are generally charged a single fee, regardless of their size or status. An exception to that rule occurs when an organization has separate operations at locations separated by more than about 500 kilometers. The policy is to charge the set fee for the base unit of that organization and to charge a reduced fee for each supplemental unit. The rationale for charging a constant fee for all base units is that a similar amount of time and effort is required to service one organization, regardless of its size. Smaller organizations are content to pay the common fee because it assures them of the same attention received by an organization several times their size.

Cooperator fees for program coordination are small compared to the expenses of tree selection, orchard establishment, orchard management, progeny testing, and deployment of seed on cooperator lands. The annual fee for the base unit of many cooperatives does not exceed $5,000. However, the industrial contributions have served as a catalyst for obtaining other monies. Some granting agencies find expediency in awarding a grant to an organization having matching monies, especially when the matching monies are of industry origin. We at North Carolina State University have received sizable grants from National Institutes of Health, the National Science Foundation, the U.S. Department of Energy, the Ford Foundation, the Rockefeller Foundation, and the National Space Administration. The monies are used to complement or extend cooperator funds.

Coordination. The major function of a cooperative program is coordination. The position is comparable to director of research for a large industrial concern. The key is to produce results today while planning for tomorrow. This task is difficult to accomplish during the maiden years of a cooperative, but it is one that nevertheless has to be accomplished. The study of wood among and within species of southern pines was chosen to fill the void in the Tree Improvement Program. That vocation melded well within the Tree Improvement Program when the larger effort began to pay dividends. For those initiating a cooperative program, many subjects allied to forestry and of equal importance to the study of wood properties await investigation.

In addition to coordination, psychology has to be practiced for development of a successful cooperative. A case in point for the Tree Improvement Program is the establishment of separate seed orchards on the land of each cooperator. A more efficient alternative would have been to establish one or a few orchards for production of genetically improved seed for all cooperators. The need for each to have separate orchards to show accomplishment and pride in their work was soon recognized. Some efficiency may have been lost, but the public relations gained from the dispersed operation have paid dividends many times over.

Coordination of a cooperative program cannot easily be accomplished without knowing what is transpiring in the profession and on cooperator lands. That accomplishment requires a tremendous amount of travel for the staff of North Carolina State Cooperatives, whose membership ranges throughout a 13-state area. Policy visits to each cooperator are made at least annually, and service visits for tree grading, grafting, pollination and progeny testing are made as needed. Participation in symposia within and outside the region also claims a significant amount of time. However, we are convinced that the contact maintained through the travel has been a large part of the success of the cooperatives.

Continuing Education. The incentive to house the administration of a cooperative program within the forestry department of a major university is twofold in addition to the university's being independent of the cooperators. These incentives are (1) ability to draw on expertise from closely allied disciplines, and (2) involvement with graduate and undergraduate education in the field of interest. At North Carolina State University, close contact is maintained with the disciplines of botany, biochemistry, entomology, genetics, horticulture, pathology, physiology, soils, and statistics, as these subjects interact with tree improvement objectives. From 12 to 15 graduate students pursuing Master of Science or Doctor of Philosophy degrees in forest genetics are annually associated with our Tree Improvement Program. Research conducted by the candidates has been instrumental in successful development of the operational tree improvement program. Graduates of this program are found in positions of influence and authority throughout the world; many of them are supervising the maturation of a second generation of forest geneticists.

A necessary ingredient of a successful tree improvement program is emphasis on continuing education. In addition to one-on-one instruction given for tree grading, grafting and progeny testing, short courses of about three days' duration are given to the technical representatives at least biennially and more often if needed. The objective of the short courses is to demonstrate tree improvement techniques and the theory behind these techniques. This effort does not substitute for a basic education in forest genetics principles; it is supplemental to the basic education.

Conclusion

The melding of many ingredients is necessary for the successful development of a forestry cooperative. The case study described for the North Carolina State-Industry Cooperative Tree Improvement Program has been successful for conditions in the southern United States. The same type of success may not be claimed in other regions of the world where differences exist in objective, environment, personnel, and political persuasion. A different melding of ingredients will probably be needed for each condition. Regardless of circumstances, however, two ingredients appear paramount to the success of any forestry cooperative. They are enthusiastic leadership and committed clientele. Without these attributes the cooperative venture is doomed to failure.

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Cone Stimulation of *Abies procera*—Evaluating Variable Rates of $GA_{4/7}$, Timing, and Girdling

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Abstract

This study investigated cone stimulation options having operational relevance to seed orchard managers. Replicated trials with five treatments were established at three orchard sites. Treatments included three variable rates of gibberellic acid $GA_{4/7}$ with girdling, one rate without girdling, and one treatment with girdling and $GA_{4/7}$ at a later treatment date. Cone and pollen production were inventoried. Results varied by orchard site. One orchard showed no relationship to treatment for either cone or pollen production. Another orchard showed treatment effect for cones but not pollen. At the third site, treatment influenced both pollen and cone production.

Introduction

Noble fir [*Abies procera* (Rehd.)], like many true firs, produces neither abundant nor frequent cone crops. Cone crops in the wild are reported at intervals averaging around 6 yr (Franklin 1983), yet pickable crops in specific desirable areas may be decades apart (J. Heater, personal communication; owner, Silver Mountain Nursery, and seed collector, Silverton, OR) with little seed available for planting. Cone stimulation trials using $GA_{4/7}$ on small Pacific silver fir (*Abies amabilis*) trees (Owens and others 2001) were encouraging, yet results relevant to larger fir in general and to noble fir in particular are unknown.

Noble fir has developed into the predominate Christmas tree species in the Pacific Northwest, replacing Douglas-fir. Currently, annual Christmas tree plantings of noble fir in Oregon alone exceed 5.3 million seedlings (Godwin 2004). Noble fir is also receiving increased attention from forest landowners. The acreage of noble fir reforestation plantings above 1,500 ft (457.2 m) elevation in Oregon and Washington is increasing, in part to replicate natural species diversity.

Noble fir seed orchards have been established at many sites in Oregon and Washington to help fill the seed needs for both Christmas trees and reforestation. These grafted orchards contain clones selected in tree improvement programs. Yet seed crop production has remained unpredictable, resulting in seed shortages and preventing capture of the full benefits from tree improvement efforts.

The objective of this research was to examine the effectiveness of $GA_{4/7}$ applications, with and without girdling, on cone production of noble fir.

Methods

This experiment evaluated the effect of five stimulation treatments on cone and pollen production in noble fir seed orchards and compared these to production in untreated trees. The treatments included three rates of $GA_{4/7}$ applied at vegetative budbreak, with girdling; one treatment at a medium $GA_{4/7}$ rate applied 2 wk after budbreak, with girdling; one treatment of $GA_{4/7}$ without girdling, and one control (table 1). This range of rates was derived from small-scale plot observations over the last decade. Rates beyond those selected caused severe yellowing and deformation of new growth (William Schlesinger and Jim Reno, Weyerhaeuser Company, personal communications). The number of cones present from the season before treatment (2003) and following treatment (2004) were counted for each tree. Pollen levels were also assessed following treatment and scored as high, medium, and low.

Experimental treatments were replicated on three noble fir seed orchard sites. Trees selected for treatment were all >5.08 cm (2 in) in diameter at breast height (DBH) and did not show evidence of heavy cone crops the previous year. Each treatment was applied to 24 selected candidate trees at each site. Where possible, all treatments were applied to ramets of the same clone. Treatments were randomly assigned to clones at each orchard position while attempting to maintain a within-clone distribution of treatments. The status of each orchard and treatment dates are summarized in table 2.

For the double-overlapping girdling, a pruning saw was used to sever the cambium layer with overlapping half-circumferential cuts on opposite sides of the stem. The cuts were spaced 1.5 × stem diameter apart and overlapped 2.54 cm (1 in) on both sides of the cut. The $GA_{4/7}$ treatment used ProCone® containing 42 µg of $GA_{4/7}$ ml^{-1}. The ProCone® was injected into holes drilled at a 30° angle 20 cm (7.8 in) above the upper girdling cut and distributed evenly around the circumference. Hole depth was sufficient to hold the volume of ProCone® in the xylem.

The operational methodology with respect to dose, volume, and application of $GA_{4/7}$ is summarized in table 3. As an example, consider the 2(E) treatment, where 20 µg of $GA_{4/7}$ is applied per inch DBH to a tree 10 in DBH. This tree received 250 mg of $GA_{4/7}$ at a rate of 20 mg. The $GA_{4/7}$ was delivered as 4.8 ml of ProCone® distributed in four drilled holes evenly spaced around the tree circumference above double-overlapping girdles.

Cone and pollen production (recorded to 1, 2, and 3) were analyzed with ANOVA for each orchard individually by a GLM procedure (SAS Institute, Inc., Cary, NC, 1998). The model included treatment (a categorical variable) and DBH as a covariate. A second model examined the relative increase in cone production by adding cone production in 2003 as a covariate. Because pollen production was a categorical variable, we also analyzed the data with a chi-square test that examined the contingency table of treatment by pollen category.

Table 1. Treatment overview.

Treatment	Girdling	µg $GA_{4/7}$ inch DBH^{-1}	Timing
C	None	0	NA
1E	Double overlap	10	At vegetative budbreak
2(E)	Double overlap	20	At vegetative budbreak
2(L)	Double overlap	20	2 wk after budbreak
3	Double overlap	40	At vegetative budbreak
2N	None	20	At vegetative budbreak

Table 2. Summary of orchard site information.

Owner, location	Approximate acreage	Year established	Mean DBH (in)	Number of clones	Germplasm origin	Treatment dates
Bureau of Land Management, Colton, OR	10	1973	12	117	Oregon Cascade seed zones 451,452, and 462. Cone production since 1993.	6/2/2003 & 6/18/2003
Weyerhaeuser Company, Sequim, WA	2	1974	11.4	53	Clone selections from seed zones 041, 430, and 440. Cone production since 1999. Good pollen yields.	5/8/2003 & 5/22/2003
Dixie PNW Christmas Tree Association, North Plains, OR	2	1995	4.3	30	Coastal Oregon sources. No prior cone crops.	5/15/2003 & 5/29/2003

Table 3. Operational summary of ProCone® dose, volume, and hole numbers by DBH class at various GA rates (10, 20, 40 a.i. in^{-1} of DBH).

DBH		Dose of $GA_{4/7}$/tree (mg) for various DBH midpoints			Volume of ProCone/tree (ml)[1]			Number of holes/tree[2]		
Average	Class	10	20	40	10	20	40	10	20	40 (2.4 ml)
4	3–5	40	80	160	1.0	1.9	3.8	1 (0.6ml)	2	2
6	5–7	60	120	240	1.4	2.9	5.7	1	2	2
8	7–9	80	160	320	1.9	3.8	7.6	2	3	3
10	9–11	100	200	400	2.4	4.8	9.5	2	4	4
12	11–13	120	240	480	2.9	5.7	11.4	2	5	5
14	13–15	140	280	560	3.3	6.7	13.3	3	6	6
16	15–17	160	320	640	3.8	7.6	15.2	3	6	6
18	17–19	180	360	720	4.3	8.6	17.1	4	7	7
20	19–21	200	400	800	4.8	9.5	19.0	4	8	8

[1] Concentration was 42 mg a.i./ml.

[2] Application was 1.2 ml of ProCone/hole (except where as noted).

Results

The results differed between seed orchard sites (tables 4 and 5). Chi-square tests on pollen production produced similar results to the ANOVA: significance levels were 0.24, 0.06, and 0.26 for the Bureau of Land Management (BLM), Dixie, and Weyerhaeuser orchards respectively. There were no statistically significant differences in DBH among the treatments at any orchard (*p* ranged from 0.23 to 0.81).

Stimulation method did not affect either cone or pollen production in the BLM orchard. The experimental trees in this block were large (table 4), and larger trees produced more pollen and cones (table 5). By design, all experimental trees had few cones in 2003. Most of the 144 experimental trees in this orchard, regardless of treatment, produced cones in 2004, with 100 trees producing 10 or more and 38 producing over 100.

In the Weyerhaeuser orchard, stimulation treatment did not affect pollen production but did affect cone production (table 5). The significance of the treatment effect for relative cone production was only p=0.112, but the significance of cone production in 2003 (the covariate) was p=0.226; indicating that it should not be in the model. A series of orthogonal contrasts designed to detect differences among treatments revealed that stimulated trees produced significantly more cones than controls (F=8.50, p=0.0045, dof=1). None of the differences among individual stimulation treatments, however, including girdled versus not-girdled, early versus late application of $GA_{4/7}$, and rate of $GA_{4/7}$, proved to be statistically significant (p>>0.05) in all cases. As with the BLM orchard, the larger trees in this orchard produced more pollen and cones.

Trees in the Dixie seed orchard were much smaller (Table 4) and not yet producing natural cone crops. Stimulation did significantly affect cone and pollen production in 2004. At the higher rates, trees showed significant yellowing, and the new growth exhibited twisting. Again, a series of orthogonal contrasts revealed that stimulated trees had significantly more cones than control trees (F=8.33, p=0.0045, df=1), but no statistically significant differences among stimulation methods were evident (p>>0.05 in all cases).

Table 4. Mean DBH and number of cones in 2003 and 2004 for each treatment and overall at each orchard site.

Orchard	Trait	Stimulation treatment						Overall mean
		C	1E	2E	2L	3	2N	
BLM	DBH (in)	13.9	13.3	14.5	13.3	14.2	14.3	13.9
	Cones, 2003	1.3	0.7	1.5	0.8	3.1	0.1	1.3
	Cones, 2004	52.0	49.0	61.8	46.0	79.1	70.7	59.8
Dixie	DBH (in)	4.5	4.5	4.4	4.2	4.2	4.3	4.3
	Cones, 2003	0.4	0.0	0.4	0.3	0.6	0.0	0.3
	Cones, 2004	1.4	6.1	8.8	13.2	6.4	4.0	6.6
Weyerhaeuser	DBH (in)	11.8	11.4	11.4	12.4	9.1	11.2	11.4
	Cones, 2003	22.3	8.9	8.3	6.4	19.6	10.8	12.0
	Cones, 2004	48.4	87.3	101.6	86.8	51.0	77.5	80.6

Table 5. The effect of stimulation treatment and DBH on cone and pollen production in 2004.

Orchard	Source of variation		Cone production, 2004		Relative cone production, 2004[1]		Pollen production, 2004	
		df	F	P	F	P	F	P
BLM	Treatment	5	0.45	0.8112	0.41	0.8387	0.93	0.4608
	DBH	1	10.59	0.0014	9.49	0.0025	12.98	0.0004
Dixie	Treatment	5	3.78	0.0031	3.77	0.0032	3.46	0.0057
	DBH	1	7.22	0.0081	6.48	0.012	1.81	0.1806
Weyerhaeuser	Treatment	5	2.36	0.0467	3.17	0.112	1.14	0.3444
	DBH	1	12.26	0.0007	7.3	0.0083	3.05	0.0841

[1] Relative production is the effect of stimulation treatment and DBH on the increase in cone production in 2004 relative to 2003.

Summary

Stimulation significantly increased cone production in two of the orchards but had no effect on the larger trees in the more mature BLM orchard. One possible explanation might be the fact that there was a “natural crop” in 2004 and for the past several years in that area. The other two orchards were located in areas outside the natural noble fir production region. Likewise, it was not possible to detect significant differences among the individual treatments on those sites where stimulation was effective.

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Enrichment of Natural Regeneration Through Direct Seeding and Fill Planting in Logging Trails of Black Spruce Stands

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Abstract

Direct seeding and fill planting of black spruce [*Picea mariana* (Mill.) B.S.P.] were assessed in logging trails after irregular shelterwood cutting in the boreal forest of Québec, Canada. Two growing seasons after harvest, direct seeding increased seedling establishment when compared to control plots, but seeded seedling density represented only 17 percent of seeds initially deposited. Seedling establishment increased with increasing soil moisture. Planted container seedlings responded well with mean terminal shoot growth of 4.7 cm (1.9 in) yr^{-1}. Terminal shoot growth of planted seedlings decreased with increasing soil moisture. Results suggest potential for improvement of logging trail regeneration with fill planting.

Introduction

In northeastern Canada, a form of irregular shelterwood cutting that protects seedlings, saplings, and small merchantable trees during harvest has been proposed to manage stands with irregular structures in the boreal forest zone (Jobidon and others 2002). This condition, often found in stands of black spruce [*Picea mariana* (Mill.) B.S.P.], is characterized by great variability in height and diameter (Paquin and Doucet 1992; Burton and others 2003). Subsequent development of treated stands has been linked to size and density of residual stems, percent area covered by logging trails, and regeneration of trails (Jobidon and others 2002).

Percent area covered by logging trails is critical because these areas tend to be less productive than residual forested strips (Grigal 2000). Soil compaction resulting from harvesting activities can reduce soil macroporosity and infiltration rates while increasing bulk density and resistance (Greacen and Sands 1980). When compaction is severe, tree root systems are negatively affected (Kozlowski 1999), reducing height (Corns 1988) and volume growth (Wert and Thomas 1981). Local effects on soil temperature and light conditions caused by slash deposits and residual trees can also influence regeneration (McInnis and Roberts 1995). Given that logging trails can often represent 20–25 percent of a harvested area with a cut-to-length system, effective regeneration of logging trails is essential to maintain stand productivity.

Artificial regeneration techniques, such as direct seeding and fill planting, could be used to supplement regeneration in logging trails. Direct seeding has been used in North America and Europe, particularly in the boreal forest (Nilson and Hjältén 2003). Seed predation, poor seedling survival, and strong competition from shrubs and herbs are disadvantages to the use of this method (Willoughby and others 2004). Direct seeding, however, is less expensive and easier to implement than planting (Wennström and others 1999).

Both regeneration techniques were investigated in this study to determine their usefulness as a complement to natural regeneration in logging trails. Two null hypotheses were tested: (1) direct seeding and fill planting are not effective in regenerating black spruce; (2) seeded seedling establishment, terminal shoot growth, and foliar nutrient concentrations of planted black spruce seedlings are not influenced by environmental conditions such as soil bulk density, soil moisture, and light availability.

Methods

Site Description. Four sites at elevations of 520 to 600 m (1,705 to 1,968 ft) in northern Québec, Canada (50º 41'N, 72º 12'W), were used. Mean annual temperature, precipitation, and frost-free days at the Bonnard meteorological station, located 80 km (50 mi) east, are -1.8 °C (28 °F), 946 mm (37 in), and 135 d (Environment Canada 2004). Length of the growing season is approximately 2 to 3 mo. All sites were in the black spruce-moss bioclimatic domain of the boreal forest vegetation zone. Undifferentiated till was the main surface deposit, and humo-ferric podzols with a sandy loam texture were the predominant soil types. Drainage was imperfect. The mean humus layer depth was 16 cm (6.3 in), varying from 12 cm (4.7 in) to 20 cm (7.9 in) among study sites.

Sites were harvested in fall 2002 with a cut-to-length system. Irregular shelterwood cutting was applied in all study sites. Trees were felled and brought in front of the harvester for processing. Slash was deposited in the trails; bucked lengths were forwarded to the roadside along a preplanned trail system. Gross merchantable volume before harvest ranged from 75 to 125 $m^3\ ha^{-1}$ (1,072 to 1,786 $ft^3\ ac^{-1}$) among study sites, and volume removal varied from 88 to 92 percent. Site preparation was not applied after harvest. Logging trails represented 22 percent of the total area of each harvest block.

Plant Material and Study Plots. Planting and direct seeding were used to assess artificial regeneration success with regard to environmental conditions. Seed and seedlings were obtained from a provincial nursery (Sainte-Anne-de-Beaupré, Quebec, Canada). Seed germination rate was 89 percent. Seedlings were container-grown (340 cm^3, 21 in^3) black spruce (2+0). Mean height (± SE) before outplanting was 60.4 ± 0.4 cm (23.8 ± 0.2 in).

In total, 15 study plots were established per site in the spring of 2003. A study plot was composed of three separate quadrats of similar substrate located within a radius of 5 m (16 ft) (figure 1). Quadrats were 1 × 1 m (3.3 × 3.3 ft). All quadrats were established on areas free of competing vegetation such as Labrador tea (*Ledum groenlandicum* Oeder) and sheep laurel (*Kalmia angustifolia* L.). One quadrat served as a control to determine natural seedling establishment. A second quadrat was used to evaluate seedbed quality by dispersing 50 black spruce seeds within the quadrat. Seeds were not mixed with the organic matter because advance regeneration was abundant on each site and severe mortality would have resulted. Environmental conditions were evaluated in a third quadrat by planting four seedlings.

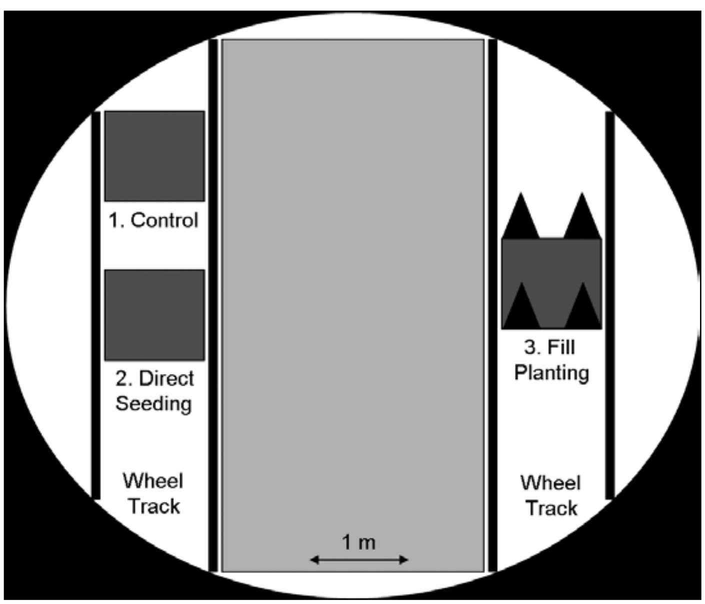

Figure 1. Schematic map of one study plot with (1) control quadrat, (2) seeded quadrat, and (3) planted quadrat located inside wheel tracks of the logging trail.

A seedling tally was carried out in the seeded and control quadrats after two growing seasons (15 mo, ~150 growing d). Total height was measured before planting, and terminal shoot growth was measured after 15 mo. In each planted quadrat, average terminal shoot growth of the four seedlings was used for statistical analysis.

At the end of the second growing season (23–24 September 2004), the terminal shoot of each planted seedling was collected and refrigerated until processed and analysed. One hundred current-year needles were selected per sample for each study plot. Samples were dried at 65 °C (150 °F) for 48 h to determine average weight of single needles (Thiffault and others 2004). Foliar nutrient samples were processed following the methods of Parkinson and Allen (1975). Total N was determined by flow injection analysis with the Quickem method (Zellweger Analytic Inc., Milwaukee, WI). P and K were determined by inductively coupled plasma analysis (ICAP-9000, Thermo Instruments, Franklin, MA).

Environmental Conditions. Light availability, soil bulk density, and soil moisture were measured in each study plot. Photosynthetic photon flux (PPF) was measured with calibrated ceptometers (AccuPAR and Sunfleck, Decagon Devices Inc., Pullman, WA). Measurements were taken on clear days between 10:00 and 14:00 on 12 and 14 August 2003, based on methods from Jobidon (1992). One ceptometer was located in the trail, just above the planted stock, and the other was placed in the center of the access road. Measurements were taken simultaneously at fixed time intervals. The ratio of light in the trails to light on the access road was used as a percentage of available light to the planted stock.

Bulk density was measured in each study plot to assess whether severe soil compaction occurred as a result of harvesting. Samples were collected in the upper 10 cm (4 in) of mineral soil with a polyvinyl chloride slip cap

10 cm in diameter and 460 cm^3 (28 in^3) in volume. Samples were taken within the 5-m radius, but not directly inside one of the quadrats. Samples were oven-dried at 105 °C (220 °F) for 48 h before weighing (Brais and Camiré 1998).

Soil moisture was measured using time domain reflectometry (Field Scout TDR 100 Soil Moisture Meter, Spectrum Technologies Inc., Plainfield, IL). Measurements were made monthly from June to August during the second growing season. Four readings were taken and averaged within each planted quadrat. The mean of all 3 mo was used as the mean soil moisture throughout the growing season.

Statistical Analysis. All analyses were conducted with SAS (Version 8.2, SAS Institute, Inc., Cary, NC). Because data for control quadrats could not be normalized, type III contrast analyses (likelihood ratio statistics) of the Generalized Models procedure (GENMOD) were used to test for significant differences ($p<0.05$) between seeded and control quadrats. A Poisson distribution, logarithmic function, and Pearson scale parameter options were specified in the model statement to account for the nature of the variables, as well as for overdispersed data. Overdispersion occurs when the data show more variability than is predicted by the sampling model chosen (Fitzmaurice 1997).

To test for the influence of environmental factors on artificial regeneration techniques, the Generalized Linear Models (GLM) procedure was initially used to detect potential site differences. This factor proved insignificant for all analyses, and linear regression was subsequently used. Seedling establishment from direct seeding, terminal shoot growth, and foliar nutrient concentrations (N, P, K) of planted seedlings were tested as a linear function of soil bulk density, soil moisture, light availability, and all interactions. The stepwise selection was used to determine the best model. Correlations, studentized residuals, and variance inflation factors were used to detect possible correlations between independent variables, test for potential outliers, and evaluate parameter estimates. Homogeneity of variance was assessed visually, and the Shapiro-Wilk test was used for normality. Logarithmic transformation was applied to seedling establishment to correct for normality.

Results

Direct Seeding. Direct seeding resulted in significantly higher density than in control plots ($p=0.0001$). The number of seedlings established after 15 mo represented 18 percent of the initial amount of seed deposited. Under natural conditions, seedling establishment was measured at 1.6 seedlings m^{-2} (10.8 ft^{-2}). With direct seeding, seedling establishment increased to 8.6 seedlings m^{-2}. After two growing seasons, however, seedlings were not much taller than 5 cm (2 in). Seedling establishment increased with increasing soil moisture ($r^2 = 0.28$, figure 2).

Planting. Survival rate of planted seedlings across all study sites after two growing seasons was 96 percent. Average terminal shoot growth of planted seedlings was 4.7 ± 0.2 cm (1.9 ± 0.1 in). Mean light availability to planted seedlings for all study sites was 84 percent, varying from 77 percent to 90 percent among sites. Terminal shoot growth decreased with increasing soil moisture ($r^2=0.20$, figure 3). Compared with averages from Swan (1970), foliar nutrient concentrations (mean ± SE, n=60)

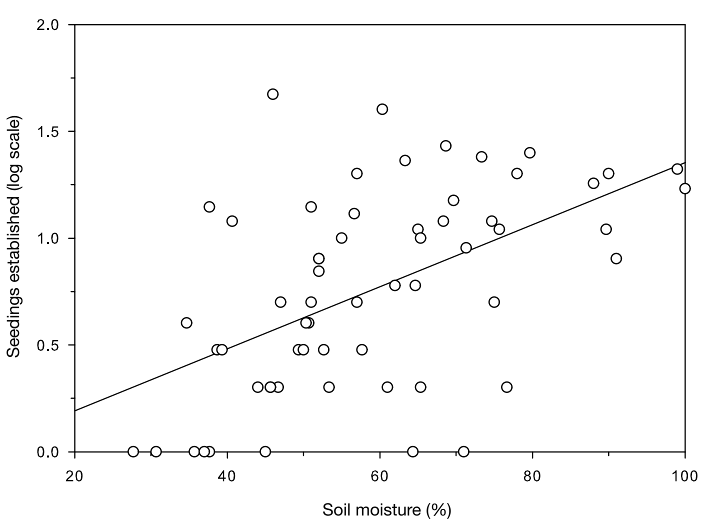

Figure 2. Number of seedlings established from direct seeding with increasing soil moisture for all study sites ($r^2=0.28$, $p<0.0001$).

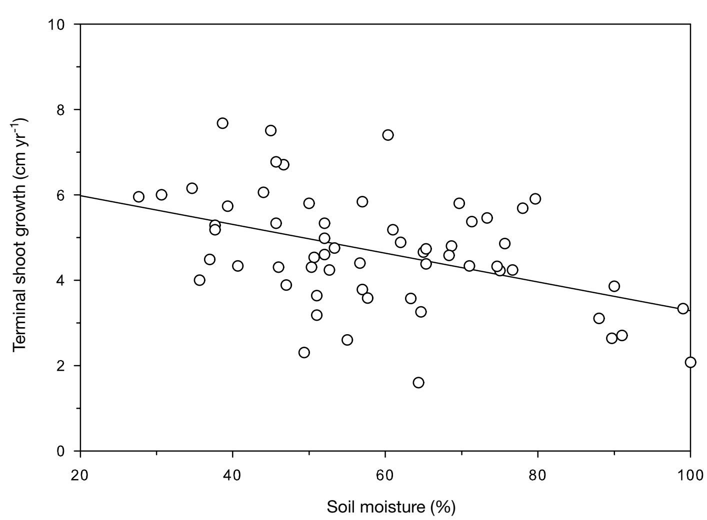

Figure 3. Terminal shoot growth of planted black spruce seedlings with increasing soil moisture for all study sites ($r^2=0.20$, $p=0.0004$).

were sufficient in K (5.1 ± 0.1 mg g^{-1} or 5,100 ± 100 ppm), but acutely deficient in P (1.0 ± 0.1 mg g^{-1} or 1,000 ± 100 ppm) and moderately deficient in N (0.9 ± 0.3 percent). Statistically significant relationships were found between soil moisture and foliar nutrients (data not shown), but the small amount of variation explained by soil moisture did not warrant further investigation.

Discussion

Direct Seeding. Direct seeding increased seedling establishment, but the percent survival remained low (18 percent). Also, seedlings were not much taller than 5 cm (2 in) after two growing seasons. Brais and others (1996) found an establishment rate of only 6 percent after direct seeding on coarse-textured sites after careful logging around advanced regeneration. The substrate type in our sites was mostly undisturbed peat moss (*Sphagnum* spp.) and feather moss (*Pleurozium schreberi* (Brid.) Mitt.), which Prévost (1997) has shown to be a receptive seedbed for black spruce. Black spruce establishment is generally favored by an organic-mineral mix or exposed mineral soil (Prévost 1996). This suggests direct seeding may be more beneficial in logging trails after moderate soil disturbance in areas where advance regeneration is poor.

Fill Planting. After two growing seasons, mortality of planted black spruce seedlings was limited to 4 percent. Terminal shoot growth was similar to values reported by Prévost and Dumais (2003) in similar sites of the boreal forest zone. Foliar nutrient analysis showed 82 percent and 90 percent of the planted stock were moderately deficient in N and P, respectively. The N levels observed in our study are comparable to those observed by Prévost and Dumais (2003) for black spruce planted without site preparation, whereas P levels are much lower. This likely will limit seedling development over a longer time because P is a major factor in energy transfer, root system development, drought tolerance, and disease resistance (Camiré and others 1996). Still, the survival rate tends to indicate that such concentrations, although quite low in some cases, may not necessarily be critical.

Planting large stock seedlings up to 50 cm (20 in) in height is usually successful on a variety of sites (Thiffault and others 2003). Fill planting could be considered as a viable option in areas of poor seed supply and insufficient regeneration on undisturbed substrate such as peat moss.

Environmental Conditions. Soil moisture was the only environmental variable that influenced seedling establishment and terminal shoot growth of black spruce. The moisture-holding capacity of substrate types such as peat moss may account for part of the positive relationship found with seedling establishment. The negative relationship with terminal shoot growth may be related to imperfect drainage of the sites. Water stress is usually caused by low moisture levels (Hébert and others 2006), but high moisture levels, such as those found in our study, can also damage black spruce seedlings by limiting root hydraulic conductance (Islam and others 2003).

In terms of light availability, a 9-yr study by Logan (1969) showed height growth of black spruce seedlings was adequate when full light was ≥45 percent. Among our study sites, lowest mean available light was measured at 77 percent. Hence, light availability inside logging trails was sufficient.

Mineral soil bulk density values reported in this study are unlikely to hinder seedling root growth. Only 10 percent of the samples were compacted to a level that could restrain root growth (≥1.25 g cm^{-3} or 78 lbs ft^{-3}), based on a study of black spruce by Prévost and Bolghari (1990).

Conclusion

Results from this study suggest direct seeding was unsuccessful in regenerating black spruce 15 mo after establishment. Fill planting was effective, and this treatment could be employed in areas of insufficient natural regeneration, seed supply, and poor seedbed receptivity. Results showed that increasing soil moisture improved early establishment of black spruce, but decreased terminal shoot growth of the planted stock. Monitoring over a longer time frame (10–15 yr) will be necessary to further evaluate the regeneration techniques in logging trails.

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Understanding Forest Seedling Quality: Measurements and Interpretation

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Abstract

Assessment of forest seedling quality has many components beyond the usual height and stem-diameter specifications found in growing contracts. Various measurements can aid in making decisions about culturing, lifting, storing, and planting. Several common morphological and physiological measurements of forest seedlings and their interpretation are described.

Introduction

The demand for bigger, better, faster-growing seedlings has been ever-growing. As a result, forest seedling production is a continually evolving technology in reforestation. Evaluating seedling quality is crucial for understanding seedling development in the nursery, as well as subsequent field growth and survival. Stock quality, however, often is assessed inconsistently and on only a limited basis. Some nurseries and reforestation managers assess their stock thoroughly each year, while others do few assessments unless a problem arises.

Although seedlings are relatively pampered in the nursery, they can have a rather perilous journey from their safe growing environment to their outplanting destination. During lifting, grading, storing, handling, and planting, opportunities for seedlings to be subject to moisture stress, temperature stress, or physical stress are numerous. These stresses are cumulative and can lead to poor field performance. When this occurs, there can sometimes be a dispute between the nursery and the landowner over what caused the poor growth, survival, or both after outplanting. Seedling quality data can assist in determining whether seedling performance issues are due to something that occurred in the nursery, improper planting practices, or environmental conditions after outplant.

Seedling quality evaluation can be used to establish benchmarks at specific points, such as time of lift or delivery, so that the nursery and the customer have a quantitative appraisal of a particular seedling lot. In addition, seedling quality data can help seedling growers and users to better understand seasonal patterns among species, stocktypes, seed lots, and cultural treatments.

Seedling Quality Assessment

There are two categories of seedling quality assessment: morphological and physiological (Mattson 1997). Morphological quality is based on the physical attributes of the seedling (table 1), whereas physiological quality is based on the seedling's internal functions (table 2). Of course, the two categories are not mutually exclusive. A seedling's morphological characteristics can be considered a physical manifestation of its physiological activities.

Morphological Quality. Morphology is used far more often than physiology to evaluate seedling quality. Height and stem diameter are the two characteristics most commonly examined on forest seedling stock (figure 1). The growing contract usually specifies a target for these two parameters, along with acceptable minimum and maximum ranges. Oddly, height is usually designated in English inches (in) but stem diameter (also known as caliper or

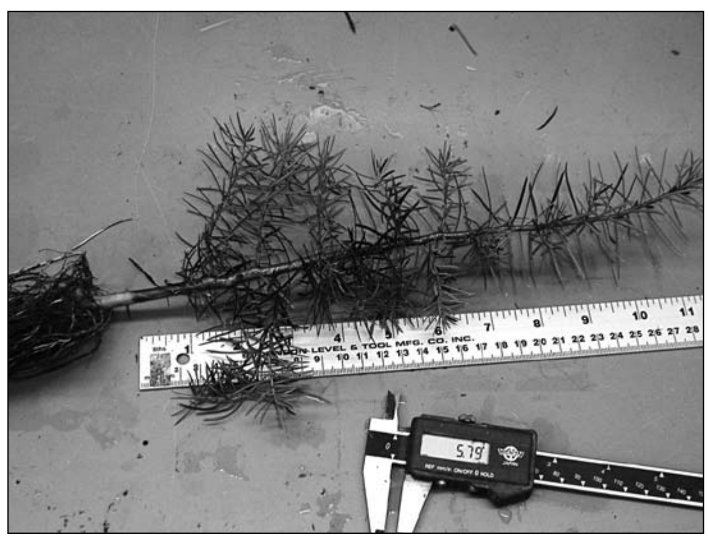

Figure 1. Measurement of height and stem diameter are the most common morphological assessments of seedling quality.

Table 1. Morphological characteristics of seedling quality

Seedling attribute	Measurement method	Units	Interpretation
Height	Measured with a yardstick or meter stick from the cotyledon scar to the base or tip of the terminal bud (or end of growing tip if no bud formed)	Centimeters (cm) or inches (in)	Shoot height is correlated to the number of needles on the seedling and therefore provides an estimate of photosynthetic capacity and transpirational area. Taller seedlings may have an advantage against severe weed competition and may indicate superior genetics. However, the greater transpirational area of taller seedlings may result in moisture stress on drier sites, especially before root establishment. Very tall seedlings may be difficult to plant, out of balance, and subject to wind damage.
Stem diameter (caliper)	Measured with a calipers just below the cotyledon scar; it's important to ensure that the calipers are perpendicular to the stem during measurement	Millimeters (mm)	In general, the bigger the better. Stem diameter has been considered the best predictor of field survival and growth. A larger diameter also indicates a larger root system and a larger stem volume.
Height: diameter	Calculation of height ÷ diameter (must use same units for each, e.g., mm/mm)	Unitless ratio	Height:diameter is a sturdiness ratio. A high ratio indicates a relatively spindly seedling while a lower ratio indicates a stouter seedling. Seedlings with high ratios can be susceptible to damage from handling, wind, drought, and frost.
Bud length	Measured with a ruler or a calipers from the base of the bud to the tip of the bud	Millimeters (mm)	Bud length is correlated with the number of needle primordia in many species and therefore gives an indication of seedling vigor and shoot growth potential.
Shoot mass	Measured as volume via water displacement (Harrington and others 1994) to include all shoot mass above the cotyledon scar or as dry weight following oven drying at 68 °C for 48 h	Volume in cubic centimeters (cm^3), or dry weight in grams (g)	Seedlings with a larger shoot mass have a greater photosynthetic capacity and potential for growth. However, a greater transpirational area may lead to moisture stress on dry sites prior to root establishment. Shoot mass must be in balance with root mass for optimum seedling quality.
Root mass	Measured as volume via water displacement to include all root mass below the cotyledon scar or as dry weight following oven drying at 68 °C for 48 h	Volume in cubic centimeters (cm^3), or dry weight in grams (g)	Seedlings with larger root mass tend to grow more and survive better than those with smaller root mass. Root mass, however, does not always reflect root fibrosity since a seedling with many fine roots can have the same mass as a seedling with a large tap root.
Shoot:root	Calculation of shoot ÷ root (must use same units for each, e.g. cm^3/cm^3)	Unitless ratio	Shoot:root measures the balance between the transpirational area (shoot) and the water absorbing area (root) of the seedlings. Generally, quality bareroot seedlings have shoot:root of 3:1 or less and quality container seedlings have shoot:root of 2:1 or less.
Color	Visual observation, or comparison with color charts	None, or color chart value	Foliar color can vary by species and time of season. Yellow, brown, or pale-green foliage can indicate lower vigor and/or chlorophyll content than dark green foliage.
Form	Visual observation	None	Existence of multiple or forked shoots, stem sweep, root deformity, stiff lateral roots, and physical damage are undesirable and can negatively affect seedling field performance.

Table 2. Physiological characteristics of seedling quality

Seedling attribute	Measurement method	Units	Interpretation
Cold hardiness	Whole plant freeze testing (WPFT) is used to evaluate tissue damage 6 d after freezing to specific temperatures. Another method, freeze-induced electrolyte leakage (FIEL), is based on the ratio of electrolytes leaked from frozen tissue to total electrolytes of killed tissue.	LT_{50}—lethal temperature for 50% of the sample; less common is the LT_{10}	Cold hardiness develops in an annual pattern similar to dormancy, with roots being much less hardy than shoots. Cold hardiness is related to stress resistance and is influenced by seed source, nursery practices, and environment.
Root growth potential (RGP)	Seedlings are potted in soil or peat media, or placed in a hydroponic tank. After 21 d in an environment optimal for root growth, the quantity and length of new roots are evaluated.	Typically divided into classes: 0=no new roots; 1=some roots, all less than 1 cm long; 2=1–3 new roots over 1 cm long; 3=4–0 new roots over 1 cm long; 4=11–30 new roots over 1 cm long; 5=more than 30 new roots over 1 cm long	RGP is influenced by stocktype, species, seedlot, and physiology and is related to field performance when trees are dead or when water uptake is dependent on new growth. However, RGP may not necessarily be expressed when under field conditions since outplanting usually occurs when soil temperatures are below optimal for root growth.
Bud dormancy	Three methods: 1) Seedlings are placed under favorable growth conditions and the number of days to budbreak (DBB) are recorded. 2) Mitotic index (MI) is assessed by placing buds in a fixative, then squashing and staining on a microscope slide. Using a microscope, the percentage of actively dividing cells is determined. 3) The bud is dissected and the number of primordia are estimated by multiplying the number of rows and columns.	Number of days (DBB); percentage of dividing cells (MI); number of primordia	Bud activity is an indicator or dormancy and stress resistance. The days to budbreak is dependent on the number of chilling hours (≤5 °C) a seedling is exposed to after budset. Mitotic index (MI) is another measure of bud dormancy and unlike days to budbreak, it does not require a long period of time to assess. MI is defined as the percentage of cells in mitosis at a given time. Owens and Molder (1973) termed Douglas-fir buds to be dormant when mitotic activity in the bud cells is zero, a condition which generally occurs from December through February.
Plant moisture stress (PMS)	A pressure chamber is the most common method for determining plant moisture stress (Cleary and Zaerr 1980).	Bars; 10 bars of PMS is equivalent to -1.0 MPa of xylem water potential	PMS indicates seedling water potential and reflects interactions among water supply, water demand, and plant regulation. PMS can be affected by time of day, species, plant age, level of dormancy and stress resistance, and environment. PMS increases with increasing moisture stress. Moderate stress can cause stomatal closure, decreased photosynthesis, and growth reductions. Severe stress can permanently damage the photosynthetic system and lead to decreased growth and survival.
Nutrients	A variety of laboratory techniques are used to determine tissue macronutrient and micronutrient concentrations. To determine content, the concentration is multiplied by the biomass of the sample.	Commonly expressed as a concentration in percent (%) or parts per million (ppm); also expressed as content in grams (g) or milligrams (mg)	Nutrient balance is important for optimal physiological processes and outplanting performance.
Chlorophyll fluorescence	The seedling's photosystem can be evaluated with pulses of saturating light by using a fluorometer.	F_{var}/F_{max} (dark-adapted foliar tissue), or quantum yield (not dark-adapted)	Fluorescence is a noninvasive, nondestructive method to evaluate plant physiology. It can provide information about the photosynthetic activity of the plant and its responses to disturbances.

root collar diameter) is referred to metrically in millimeters (mm). The contract specifications for height and stem diameter are then used to grade seedlings as packable or cull. Workers on the grading line should be trained to also cull seedlings with physical deformities, mechanical damage, and signs of disease (e.g., dead tops or blackened roots).

Height and stem diameter are easy and quick to measure and can be a good estimate of seedling quality and subsequent field performance (Omi and others 1986; South and others 1988; Mexal and Landis 1990; Rose and Ketchum 2003). These two shoot measures alone, however, are inadequate to assess the seedling condition fully. Although stem diameter is well correlated with root system size, root development usually is not directly assessed other than by a cursory observation on the grading line. Unfortunately, measures of root quality are not as quick and simple as those for shoot quality and require a subsample evaluation separate from the grading line in order to assess root size and form accurately (table 1, figure 2). The root system should not be overlooked, however, since it can profoundly affect seedling growth and survival after outplanting (Rose and others 1997; Jacobs and others 2005). Another morphological aspect that should not be overlooked is seedling balance. Even if height and stem diameter are on target, the seedling could be very unbalanced. It is important that the shoot not be too tall relative to the stem diameter (figure 3) and that the shoot mass not be too large relative to the roots (figure 4).

Physiological Assessment. Simple height and diameter assessments are also ineffective in estimating seedling physiology (table 2), especially when there has been a stress that can seriously compromise seedling quality. The most common inquiries I receive regarding conifer seedling quality are after an early fall freeze (such as the severe Halloween freezes in 2002 and 2003, which significantly damaged many Pacific Northwest crops). Because seedling shoots are not actively growing in the fall, freeze damage can be difficult to discern; as long as conditions are cool, seedlings can remain green for quite some time despite significant damage. As a result, dead or damaged seedlings can make it through the grading line and be shipped for outplanting. A simple option to evaluate damage following a freeze is to collect a representative sample of 15–20 seedlings from each lot in question and pot them. Keep the potting medium moist and place the pots in a warm environment. After 6–7 days, using a razor blade, examine the cambium

Figure 2. Seedling root and shoot volume can be measured via the water displacement method; these data can be valuable for determining root development and overall seedling balance.

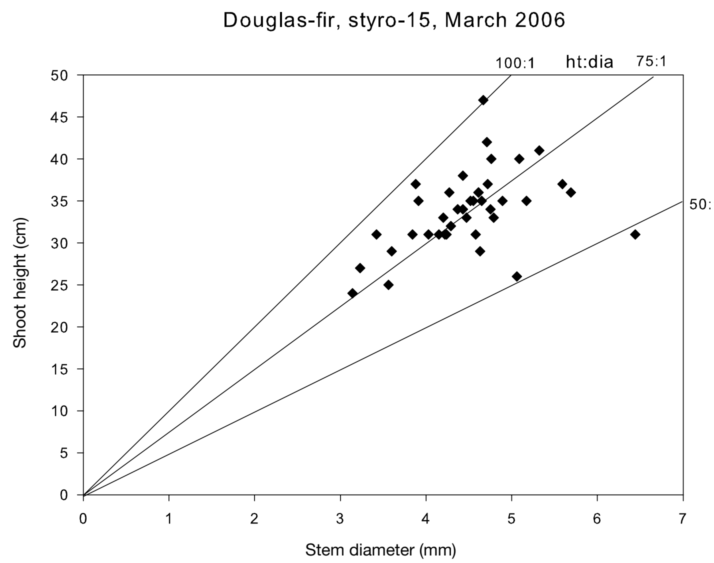

Figure 3. The ratio of height to stem diameter provides information about the seedling's sturdiness.

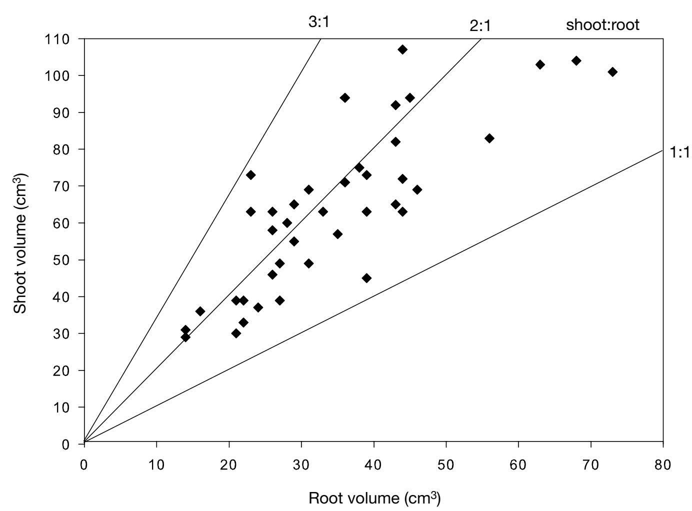

Figure 4. The balance between the seedling shoot and root is often critical to subsequent outplanting performance.

and buds. Any browning in either tissue indicates freezing damage. From there, the nursery manager or customer can decide whether or not to keep the crop. If damage is minimal and the crop is kept, lifting could be delayed to allow recovery, seedlings could be outplanted to a site with low stress conditions, or both.

Cold hardiness is likely the most useful physiological quality test available. Cold hardiness testing can provide a good estimate of stress resistance for a given seed lot (Faulconer 1988, Burr 1990). To test for hardiness, groups of seedlings are placed in a programmable freezer. The temperature in the freezer is decreased gradually from room temperature to a target subfreezing temperature and held for 2 h. Four target temperatures are selected on the basis of their expected ability to create a given range of damage. Similar to the procedure described for assessing damage after a fall freeze, seedlings are then placed in a greenhouse with adequate moisture and warm temperatures for 6 d, after which damage to foliage, cambium, and buds is evaluated (figure 5). If the cambium is dead in the mid- to lower section of the main stem or if more than 50 percent of the buds are damaged, the seedling is considered nonviable (Tanaka and others 1997). From these data, the lethal temperature to 50 percent of the seedlings is estimated (figure 6).

Root growth potential (RGP) is another popular physiological test to evaluate seedling vigor (figure 7). It is useful for determining the percentage of live or dead seedlings in a particular lot, but there is some debate regarding its usefulness in predicting subsequent field performance (Simpson and Ritchie 1997). RGP is determined after 3 wk under ideal environmental conditions. Seedlings are rarely outplanted to optimum temperature and moisture conditions, however, and therefore will likely have a lower expression of root growth in the field.

Other physiological tests include the following:

- Plant moisture stress (PMS), which is an indicator of xylem water potential and is often used to schedule irrigation and monitor water stress during lift and pack operations (Lopushinsky 1990) (figure 8);
- Bud development, which is related to seedling dormancy and shoot growth potential for the following season (figure 9);

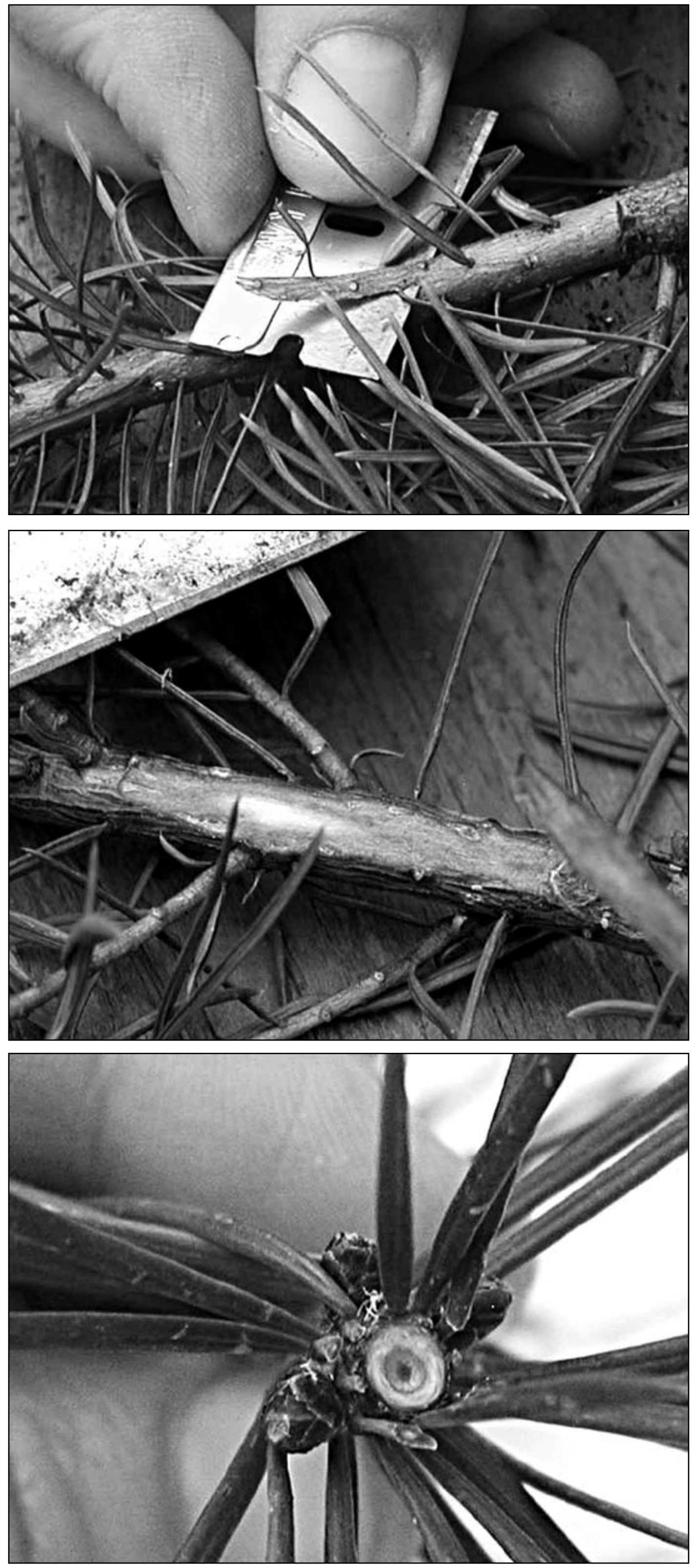

Figure 5. Examination of damage to bud and cambium tissue following freezing at specific temperatures determines the seedling's viability.

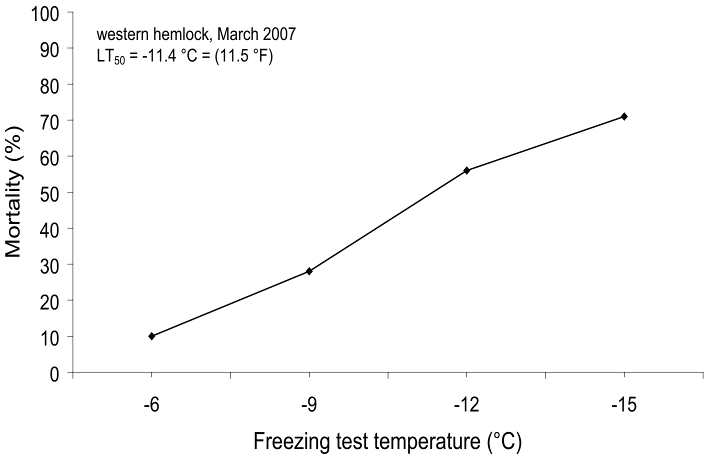

Figure 6. Cold hardiness (LT_{50}) is estimated by assessing the level of seedling mortality across a range of freezing temperatures.

Figure 7. The length and quantity of new roots generated during a 3-wk period under optimum growing conditions is used to assess RGP.

Figure 8. A pressure chamber is used to determine the xylem water potential of a seedling branch sample.

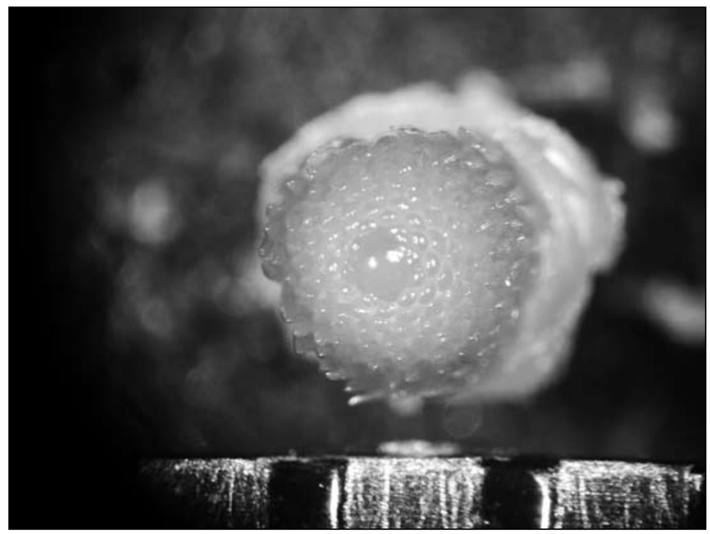

Figure 9. The number of bud primordia present in a seedling bud determines the number of new needles that will form in the following growing season.

- Chlorophyll fluorescence, which indicates a seedling's photosynthetic activity (Mohammed and others 1995); and
- Nutrient status, which governs many metabolic processes in the seedling.

Seedling Quality Testing Facilities. At the very least, nearly all nurseries evaluate height and stem diameter of their stock. Some nurseries also conduct more intensive in-house seedling quality evaluations on a portion of their seed lots. With the exception of several laboratories that offer nutrient testing on plant tissue samples, there are very few third-party seedling quality testing facilities in the country. The Nursery Technology Cooperative (NTC) established a regional forest seedling quality testing facility at Oregon State University (Corvallis) in 2000. Those who use the service are pleased to have an objective resource available to provide the requested data in a timely manner. Currently, services available through the NTC program include morphological evaluation (height, stem diameter, height:diameter, root and shoot volume, shoot:root) and cold hardiness determination (whole plant freeze test). Further information can be found at http://www.cof.orst.edu/coops/sqes.htm.

Conclusions

Many morphological and physiological variables can be monitored in order to track and assess seedling quality. A comprehensive evaluation regime provides useful data for aiding management decisions and understanding effects of culturing, handling, or environmental stress events. Through inhouse programs or third-party services, seedling quality evaluation is a valuable tool for both nurseries and reforestation personnel.

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Achieving Establishment Success the First Time

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Abstract

Planning a planting project to achieve a high probability of success the first time, though it may cost a little more up front, will pay off in dollars, effort, and time to the final product—all of which mean higher investment returns. A set of principles are reviewed that are central to a successful planting project, focusing in particular on choosing the right planting stock, handling them properly from the nursery to the planting hole, and tending the trees after planting.

Introduction

Every grower's goals and conditions are unique, but the importance of *successful establishment the first time* (figure 1) characterizes every planting project. A key component of success the first time is choosing healthy, vigorous planting stock of the right size and condition for your needs. This article will help you understand your planting stock options and share with you some "insider information" about key indicators of planting stock vigor and success factors that might not be evident from a quick glance at the seedlings.

Figure 1. A Douglas-fir seedling after 5 yr in the field, illustrating "Success the First Time." (Courtesy of Weyerhaeuser Company photo archives)

Success means growing the product your customers want, in the shortest possible time, at the lowest cost required. Getting a good start on your project—getting it right *the first time*—not only increases your returns but can save you money over the life of your project, even though it might cost a little more up front.

First, as you define success, remember: time is money. You could have put the money spent to buy seedlings, prepare and plant your field, and tend your trees into an alternative investment with a certain rate of return—or you could have borrowed the money at a certain interest rate and need to think about how much return you need to pay the interest. The longer you have to wait to harvest your crop and take the payback, the higher the carrying cost of that compounding interest or the alternative rate of return. To make even 6 percent on your planting investment, you need to make $1.80 at year 10 for every $1 you invested up front. To make 10 percent, you need to bring in $2.60 at year 10 for every dollar you invest up front. By the same logic, if you could make that $2.60 in 8 years instead of 10 years, your return would be 13 percent instead of 10! Time really does mean money.

Given all the costs of starting a new plantation, and the long waiting period before a timber harvest, it's often tempting to try to economize. In the case of establishment success, the temptation to start cheap can cost you more over the total project, especially considering the carrying cost of money. Consider the following examples.

In the "Right the First Time" case, shown in table 1A, we invest in 2 yr of weed control around the trees, good-sized healthy seedlings, and a quality planting job. These costs can add up—in this case, nearly $350 per acre. (Of course your own regime and costs may be different.) To make even 6 percent on our investment over a 50-yr timber rotation, we would have to net $6,401 per acre.

In the "cheap way," shown in table 1B, we "economized" with only 1 yr of weed control and smaller, less expensive planting stock. Sure enough, in this case we can get away with $70 per acre less cost up front. *However*…the lower quality stock and extra weed competition is likely to

Table 1A. An example of cost and revenue for a planting project done "right the first time."

"Right the First Time"	
2 yr intensive vegetation control	$100
Plant 350 trees	$248*
Total cost, Yr 1-2	**$348**
Revenue needed to make a 6% rate of return in 50 years	***$6,401***

*$0.30 cost for each seedling, $0.20 per tree for planting.

Table 1B. An example of cost and revenue for a planting project done "the cheap way."

The "Cheap" Way	
Spot weed control	$50
Plant 300 trees	$135*
Total Yr 1	$185
But then, 1 yr later….	
Replant 200 TPA	$140**
Respray	$75
REAL total Yr 1-2	$400
Revenue needed to make a 6% rate of return in 52 yr	$8,027
Extra cost of money at 6%	***$1,626***

*$0.25 cost for each seedling, $0.20 per tree for planting.
**$0.35 cost for each seedling, $0.35 per tree for replanting.

result in considerably more mortality, requiring a replant to utilize the field fully and another spray to ensure that the additional trees will survive. Over the same 2 yr, we would end up spending $50/acre MORE than we would have to do it right the first time—and we've lost 2 yr on the production cycle, so now we have to carry our investment for 52 yr instead of 50. Now we'll have to earn over $8,000 per acre instead of $6,400 to make the same 6 percent on our investment.

What Is Required To "Do it Right the First Time"?

Four elements are required to "do it right the first time":

- Good ground preparation: site selection, drainage, nutrition;
- Vigorous planting stock: the right size and type for your objectives;
- Proper seedling storage, handling, and planting; and
- Full control of competing vegetation before and for at least 2 yr after planting.

Think of your seedlings as a biological "bank account." The size of the first deposit depends on the size, balance, and physiological condition of the seedlings you select. Beginning with lifting the trees at the nursery, we start to make "withdrawals." The nursery helps to minimize withdrawals by lifting at the right time, culling the poor trees, handling the seedlings carefully, minimizing exposure, and using proper storage conditions. You can add to the bank account by selecting the right site; using good ground preparation, including drainage as needed; controlling weeds; and adding fertilizer if a soil test calls for it. You can minimize withdrawals by carefully managing storage and handling of the trees, doing a quality job of planting, and protecting them from deer browse and weeds.

What Are Your Choices for Planting Stock?

What are your choices when it comes to planting stock for the best up front "deposit" in your stand's biological bank account? You need to consider external features of your stock—things like seedling size, stock type, and grade—as well as internal features relating to the seedlings' physiological condition, which influence cold and stress tolerance and the vigor of roots and shoots (ready to grow at the right time after planting).

The Ready-to-Grow Seedling. Let's start with some "first principles" of a healthy, vigorous, ready-to-grow seedling.

1. *Root system morphology*. Survival after planting depends on the roots being able to take up more water than the top transpires. Development of a lot of fine-root mass (moppy roots) is the key. We look for a root system like this because new, fine roots have more surface area and better water uptake than older woody roots after planting (figure 2).

2. *Root-shoot balance.* The larger the top, the more transpiration demand is placed on the roots. If roots can't take up enough water, photosynthesis stops and trees begin to lose needles and die back from the tops. Conversely, if roots *can* absorb water quickly and efficiently the tops can photosynthesize more, producing more energy to fuel growth of new roots and tops (figure 3).

3. *Seedling caliper (diameter at root line).* A conifer stem is made up of tracheids—hollow pipes that transport water from root to top. Water is pulled up the pipes—into the roots, up the stems and out through the stomates or leaf pores—in very narrow columns by the tension that is generated by the demand from the atmosphere. In dry, hot conditions, the tension can be so high that water columns break, which leaves pipes unusable, at least for a time. The stouter the stem, the more redundant plumbing the seedling has to carry water from the roots to support the top under stressful conditions. Larger caliper seedlings also tend to have more foliage and energy reserves, and so typically grow more at the start than smaller seedlings (as long as water availability through the roots is able to keep up).

Figure 2. A seedling root system showing moppy form, with plenty of branching and fine roots.

Your Choices in Stock Types. When you go to purchase seedlings, you'll be faced with an array of "stock types." "Stock type" refers to the growing regime of the tree and drives the morphology and performance you can expect. The most common choices are bareroot stock and containerized stock.

Bareroot stock. The tree was grown for 1–3 yr in an outdoor bed and delivered dormant with the soil gently shaken from the roots (figure 4).

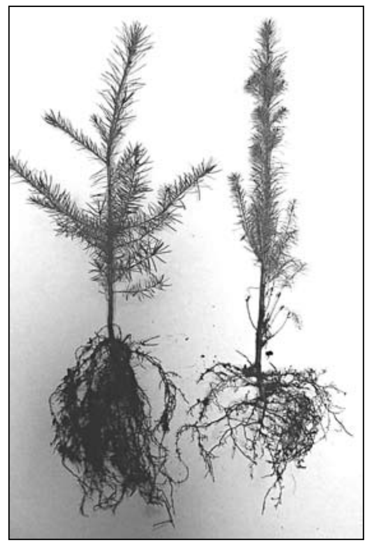

Figure 3. Two bareroot seedlings grown with different regimes and providing different root-shoot balance. Note the coarser and less branched roots in the 2+0 seedbed seedling to the right, compared with the well-balanced 1+1 transplant seedling on the left.

Figure 4. A 2-yr-old bareroot transplant Douglas-fir seedling.

- Seedbed only—sown and grown to lifting in place in the bed, usually at a fairly high density.

- Transplant—sown and grown for 1 yr in seedbed, then lifted and transplanted for 1–2 additional yr at lower density in a transplant bed.

Terminology:

1+0 or 2+0 refers to seedbed stock grown 1or 2 yr before lifting and delivery. 1+1 or 2+1 refers to stock grown 1 yr or 2 yr in a seedbed, then lifted, graded, and transplanted for 1 yr, usually at lower density, in a transplant bed (figure 5).

Advantages:

- Typical bareroot transplants are often larger and woodier than container seedlings, with more lateral branching, which can make them more tolerant of sites with heavy brush or animal browse.

- Because of their initial height and caliper advantage over containers, they can offer excellent performance for the cost if they can link up quickly and survive to the fall root-growth period. *Maximum volume of moppy, healthy roots and good root-shoot balance out of the nursery are critical in a bareroot seedling.*

- Size for size, bareroot seedlings cost less than container stock to buy, store, and ship because they don't carry soil on their roots.

Disadvantages:

- Bareroot trees must depend on existing roots to hold them over until new roots can develop, and they tend to be slower to initiate new roots in cold soils. The older roots are not as efficient in water uptake, so for a time these trees will be at higher risk of mortality on sites with heavier soils; warmer, drier, or windier conditions; or infrequent rain.

- The normal process of lifting, sorting, and planting bareroot stock can cause accumulated low-level damage to tissues. As a result, this stock will often show "planting shock"—a lag period when roots must recover and grow before the top will emerge and grow vigorously. This can be the entire first growing season if conditions are less than favorable.

Figure 5. 1+1 bareroot seedlings in an outdoor nursery bed, nearing the end of their second growing season.

Containerized stock. These seedlings are grown indoors in containers, extracted, and shipped with the soil "plug" intact around the roots (figure 6).

Terminology:

Unfortunately, multiple naming systems have arisen for container seedlings. Containers may be described by the number of cells in the growing tray (112, 160, 198—the larger the number, the smaller the seedling), by the volume of the plug in cubic inches (styro 8, styro 15—the larger the number, the bigger the seedling), or by the diameter and length of the plug in centimeters (412, 515—the larger the number, the bigger the seedling) (figure 7).

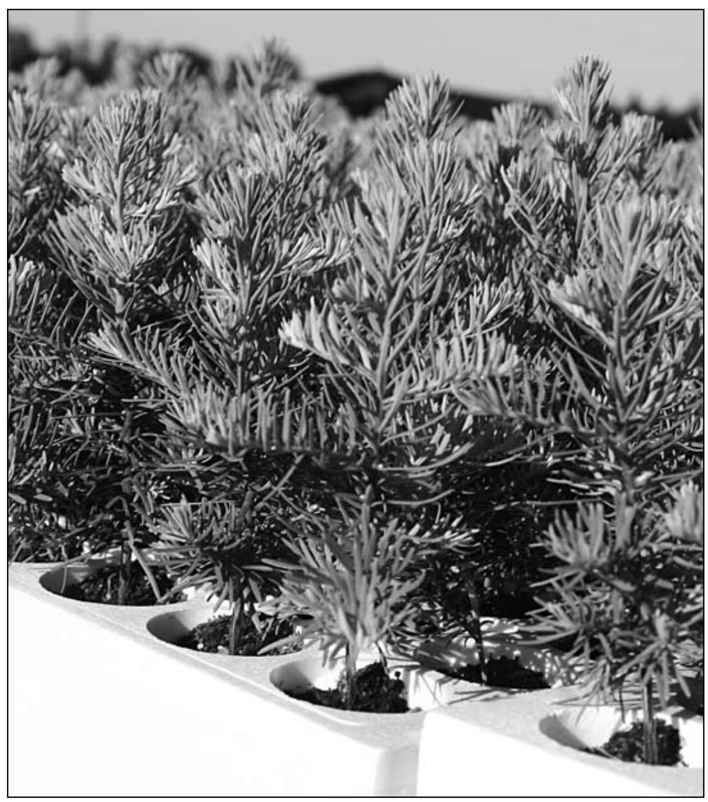

Figure 6. Containerized noble fir seedlings before lifting and packaging from their styro blocks.

Advantages:

- Because the seedling's roots are protected from drying and root damage during packing, they tend to proliferate more quickly even in cold soil (plenty of ready-to-grow root tips).

- The soil-root contact and greater number of fine roots that come with the plug give containers a better start when water stress is high (figure 8).

- Because of the intact root plug, they can be planted properly with less effort on shallow, rocky, or heavy soils.

- They can be made to set bud early with "dark-out" to support late summer or fall planting.

Figure 7. A containerized western redcedar seedling in a Styro-15 plug.

Figure 8. A containerized seedling a few weeks after planting—note the proliferation and rapid elongation of new, efficient roots.

- Some slow-growing or small-seeded species can only be grown to large size economically if started in a container. The more stressful the site and the more important early growth is, the greater is the advantage of container stock.

Disadvantages:

- Size for size, container stock is considerably more expensive than bareroot, and transporting the weight and mass of the soil plug also adds cost.

- Most containerized stock types are shorter and less robust than bareroot, with fewer buds and less lateral branching, making them more vulnerable to clipping by rodents or browsing by deer or elk.

Other Considerations. Several other factors should be considered in selecting seedlings.

Culling standards. Most planting stock is graded against specific standards for height, caliper, and balance and pruned to a specified root-length standard when it is packed. Ask your nursery to describe the culling standards they used and inspect the stock in several bags to ensure they consistently meet the standard. A small or unhealthy tree will mean more rework!

Seedling conditioning. Seedling vigor after planting is strongly impacted by dormancy, stress resistance, and cold hardiness—a suite of traits that together can be referred to as "conditioning." Dormancy peaks in late autumn, but cold hardiness and stress resistance are at their highest in midwinter. What do these terms really mean and how do they matter?

Dormancy is a measure of bud condition and readiness to flush. When buds are fully dormant, they will not flush for weeks, even when placed into spring-like conditions. Once buds begin to flush, the energy produced through photosynthesis is diverted from roots into the new growing shoot, temporarily shutting down root growth. At optimum dormancy, the buds will remain at rest for a time after planting, allowing roots to emerge and link the tree with the soil before the buds flush. Dormancy is released as trees are exposed to warm temperatures through the winter and early spring. A seedling lifted and delivered too early or too late may flush immediately, putting too great a demand on the root system and leading to mortality as the weather gets warm and dry.

Cold hardiness and stress resistance result from changes in the plant's cells after the seedling stops growing, sets a bud, and is exposed to chilling through the fall. The changes, which typically peak in early winter, leave the plant able to withstand cold temperatures and handling stress much better than it could earlier or later (figure 9).

These elements of seedling conditioning are driven by a complex sequence of events—some controlled by the nursery grower and some by you. Luckily for the seedling buyer, knowledge and techniques to maximize seedling conditioning have advanced dramatically in the past 10 yr.

Stock is well conditioned when it has received the right signals for dormancy to develop, tissues have developed good cold and stress hardiness, and dormancy release has not progressed too far. The timing of lifting in the nursery really matters. Late lifting or early lifting can mean low stress tolerance, vulnerability to cold damage, and buds that will flush too soon, preventing normal early-spring root growth. Storage also plays a role. Seedlings lifted early can be chilled more in cooler storage, thus bringing them to the optimum hardiness and dormancy. Seedlings lifted at the optimum time can be held in the cooler for 4–6 wk until the best time for planting, though they will slowly decline in conditioning. Techniques have also been developed to hold stock "in stasis" in the freezer at 25–28 °F (-2 to -4 °C).

Some knowledge of storage and lifting guidelines can make you a more knowledgeable seedling buyer and can make a real contribution to planting success. Ask how your stock was conditioned before lifting—how and when was it shut down, and whether sufficient time and chilling was allowed for. Ask when your stock was lifted and how long it was stored. Inspect your stock for well-developed buds, stiff woody stems, dark green waxy needles—all evidence of a good conditioning regime. And don't forget to look for the "moppy" roots!

Protection from frost and disease. Nurseries are farms and, as such, can be subject to damaging temperatures and soil diseases. Seedling nurseries can protect their stock, like many other crops, from damaging cold through the fall by sprinkling the trees with water through the cold periods. The constantly freezing film of water maintains the stems and foliage at undamaging temperatures. Also, ask your nursery about their disease prevention and treatment program. If they don't have one, your trees are at risk. If not managed carefully, fungi can build up and kill fine roots, leading to poor survival and growth. Inspect your seedlings by stripping several roots—if the bark peels off easily, leaving brown tissue, they are dead; if the inner tissue is white they are alive.

Don't accept seedlings that have storage mold growing on the lower needles when you open the bag. The needles will not be healthy and stem tissue may have been killed.

Stock Handling and Planting

Remember that seedlings, even dormant bareroot ones, are alive! Even well-conditioned trees are vulnerable to damage and exposure during handling and planting. The way you handle your seedlings after you pick them up from the nursery is vital in their survival and early vigorous growth (figure 10).

Figure 9. This well-conditioned seedling has a stout stem, well-developed buds, and dark green needles with well-developed waxy cuticle, able to tolerate the stress of handling and planting on tough forest sites.

Figure 10. Hand planting of bareroot seedlings on a forest site. (Courtesy of Weyerhaeuser Company photo archives)

First, exposure to warmth and breeze can dry out roots to the point where survival and growth can suffer. Once you receive your trees, keep them moist (*not* wet), out of the sun and heat. Don't store your stock in water—that will kill roots. Also, very wet, muddy conditions during storage can promote disease buildup. Rough handling can reduce vigor of roots and shoots, so treat your seedlings gently, even in the bags. Seedling bags should be kept below 35 °F (2 °C) during storage and transport and stored no longer than 4–6 wk. If you need to keep them longer, they can be frozen at 26–28 °F (-2 to -4 °C). In all cases, get them in the ground as soon as you can—but don't try to plant when it's warm, windy, or very dry. Even a few minutes out of the bag under these conditions can kill or cripple a seedling.

Next, make sure you plant your trees with care. Be sure that the tree is planted to the root collar; exposed roots can wick water right out of the seedling. Close the planting hole so that there are no air pockets around the roots, but without heavily compacting the soil around the trees. Wadded or J-roots can lead to poor or asymmetrical root growth, which can lead to poor tree growth and instability later. Handle the trees gently—that means no beating roots on stumps, no ripping roots apart, and no holding them out in the air for an extended time during planting. Closely oversee your planting crews during the planting, and spend the time up front to make sure they understand your quality expectations (figure 11).

Finally, keep the grass and weeds away from your seedlings. Their thick roots will suck up the water that your seedlings need during the crucial early years. The best results will come from a broadcast weed control application, tilling out the weeds before planting and hoeing or spraying all the vegetation for at least 2 yr after planting. If the weeds and grass aren't too thick, you may be able to get away with spraying or pulling the weeds in a spot 3–4 ft (approx 1 m) in diameter around each tree. If you use herbicides, choose the product carefully. Some herbicides can be sprayed over young seedlings if they're dormant, but some can cause serious damage; some also need to be kept strictly away from wells and streams. And, of course, read and follow all label requirements for mixing, application, and cleanup for that specific product.

These basic steps, if consistently followed, will take you well down the road to a vigorous, effective plantation *the first time* (figure 12). Good luck, and happy growing!

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Figure 11. Planting shovel and properly planted seedling. A proper tool is critical to a good planting job.

Figure 12. Vigorous, well-conditioned seedlings, properly planted with good weed control, now starting their second year of growth. Success the First Time!

A Reference Library for Readers of *Tree Planters' Notes*

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This article is aimed at anyone who might be interested in putting together some books for everyday use as reference tools. Certain books always seem to be of value in answering questions or as a means to refresh one's memory about how to figure something out. Some books are just fun to own because of their historical significance, whereas others help with technical calculations.

Because I have yet to come across a good reference list for reforestation and nursery managers in an article in *Tree Planters' Notes* or elsewhere, I have started the following list. It is a modest list of books you may have heard of or may have never known existed. I have developed this list during my long career, so some books might be hard to find these days. All, however, will have some usefulness. The reference for each is given, along with a short description of what it contains and how it might prove useful. You might just go to the RNGR Team site (pronounced 'ringer') at http://www.rngr.net/Publications and have fun looking around at all of the free information. RNGR stands for **R**eforestation, **N**urseries, and **G**enetics **R**esources and is the home of *Tree Planters' Notes*.

The Forest Nursery Manual: Production of Bareroot Seedlings. M.L. Duryea and T.D. Landis (eds). 1984. The Hague: Martinus Nijhoff/Dr W. Junk. 385 p. Although this book was written years ago, it is still very useful to bareroot and container growers alike. In terms of concepts and theories, it will probably never go completely out of date. Every chapter was written by a known expert of the time who understood present, as well as future, needs. Believe it or not, you can download this book at the RNGR Team Website (http://www.rngr.net/Publications/fnm)! Finding a hard copy can be difficult and expensive.

The Container Tree Nursery Manual. T.D. Landis and others. 1990 onward. Agriculture Handbook 674. Washington, DC: U.S. Department of Agriculture (USDA) Forest Service. Various pages. This manual consists of seven volumes: Volume 1—Nursery Planning, Development, and Management; Volume 2—Containers and Growing Media; Volume 3—Atomospheric Environment; Volume 4—Seedling Nutrition and Irrigation; Volume 5—The Biological Component: Nursery Pests and Mycorhizae; and Volume 6—Seedling Propogation. Volume 7 is still in production. Volumes 1 to 6 are free for the downloading from the RNGR Team Web site (http://www.rngr.net/).

Planting the Southern Pines. P.C. Wakeley. 1954. Agriculture Monograph No. 18. Washington, DC: USDA Forest Service. 233 p. If you can find a copy of this in hardback at an antique book store, buy it! Not only is this book a gem to read, but you learn that, after more than 40 years, we still have a lot to learn about growing and planting seedlings. One secret is physiological condition—not just seedling morphology. A classic comment from Phil Wakeley: "The surest means of attaining success in planting is to keep all phases of the process in balance." Another to always remember would be "The fact that physiological qualities differentiate *internal* seedling conditions must be emphasized."

Reforestation Practices in Southwest Oregon and Northern California. S. Hobbs and others, eds. 1992. Corvallis, OR: College of Forestry, Oregon State University. 465 p. For westerners, this is a great book summarizing the reforestation outcomes of the Forestry Intensive Research program. The title leads readers to believe it is only useful for limited areas in Oregon and California. In truth, the chapters are rich with information on theory, processes, and concepts that work all over the world. It is still available from Forestry Communications, College of Forestry, Oregon State University, Corvallis, OR 97330 (e-mail: ForestryCommunications@oregonstate.edu).

Regenerating Oregon's Forests. B.D. Cleary and others. 1978. Corvallis, OR: Oregon State University Extension Service. 287 p. This is the classic forest regeneration book and one of the first of its kind. Unfortunately, it is out of print. While much of what it spoke to in terms of seedlings is very much out of date, the concepts it teaches are valid. In the West and elsewhere in the United States and Canada, seedlings have gotten much bigger and come in an infinite variety of sizes and costs. If you ever see a copy of this book in a used book store, buy it! Other organizations have copied this book for other parts of the United States and Canada.

Tropical Tree Seed Manual. J.A. Vozzo, ed. 2002. Washington, DC: USDA Forest Service. 874 p. Dr. Vozzo did an outstanding job with this book. It weighs around 5 lbs! It is an amazing encyclopedia of information and well worth having on the shelf if you grow plants or work in tropical areas. The authors created an information source that will be useful for decades, especially to those wanting to grow and plant the world's dwindling tropical forests. You can download this book for free at http://www.rngr.net/Publications/ttsm.

Mineral Nutrition of Higher Plants. H. Marschner. 1989. Orlando, FL: Academic Press. 674 p. If you do fertigation or just want to know how nutrients behave in plants, this is a great reference to keep on the shelf in the office. Ever wonder about ammonium versus nitrate nutrition? This book has some answers, along with lots of references. You will even find lots of facts on other subjects, such as "root elongation rates as a function of soil strength (resistance to root penetration)." Although a college level text, this is a great reference.

Plant Biomechanics. K.J. Niklas. 1992. Chicago, IL: University of Chicago Press. 607 p. For those of you who are more cerebral, this book comes highly recommended. This is a great book for graduate students. It is probably one of the best written books about a difficult subject area. Aspects of it will be over the heads of those without calculus and physics. Most of the book, however, is written with such clarity that a disciplined reader will get much from it. This book has wonderful explanations of how water moves in and is utilized by plants.

Hartmann and Kester's Plant Propagation: Principles and Practices (7th ed.). 2002. Englewood Cliffs, NJ: Pearson-Prentice Hall. 880 p. This book has been around a long time. The 2nd edition has been good enough for some of us that we never bought the next five. Sometimes one just needs a good book on cuttings, general media information, and more. The title says it all.

Seeds of Woody Plants in the United States. C.S. Schopmeyer, tech. coord. 1974. Agricultural Handbook 450. Washington, DC: USDA Forest Service. This book has been around a long, long time. A lot of libraries have it, and occasionally you will find one at a used book store. It has been around so long that there are no copies available. The Forest Service, however, will be printing a new updated version—The Woody Plant Seed Manual (Agriculture Handbook 727)—in 2008. I even have the original Woody-Plant Seed Manual (1948), which was labeled Miscellaneous Publication No. 654.

The Herbicide Handbook (7th ed.). 1994. Champaign, IL: Weed Science Society of America. 352 p. Everyone in forest regeneration who works with herbicides should have this handbook. This is a very useful reference for all sorts of esoteric information about various herbicides. This book provides information on manufacturers, herbicide use, precautions, behavior in plants, behavior in soil, and toxicological properties. Do you know what a dermal LD_{50} of 1,122 mg/kg means?

The Dictionary of Forestry. J.A. Helms. ed. 1998. Bethesda, MD: Society of American Foresters. 210 p. If there is one thing that can bring clarity to a conversation, it is the use of words with definitions everyone accepts. How ironic that this book does not have the definition of a seedling in it! It does, however, contain lots of other words and expressions. By the way, the legal definition for seedlings in Oregon is "live trees of acceptable species of good form and vigor less than one inch in DBH"…just in case you were wondering. Lawyers have their definition of a seedling, and we have ours.

Media and Mixes for Container Grown Plants. A.C. Bunt. 1976, 1988. London: Unwin Hyman Ltd. 309 p. This book is fabulous! Anyone in the container business in a serious way should attempt to find this book and pay what is asked for it. Bunt created a mini-encyclopedia in 309 pages. If you thought you knew media, this book will show you how much more you have yet to learn. The problem is that the last time I checked the price it was $220 per copy, and there were only two copies left.

Physiological Plant Ecology. W. Larcher. 2001. Berlin: Springer-Verlag. 513 p. This fourth edition is masterfully done, but why would someone in nurseries or reforestation want a book like this? Physiological plant ecology is a subject that foresters can benefit from regularly. This book covers the gamut from carbon sequestration to soils. So much of the science in forestry these days is being interpreted in terms of carbon and ecological modeling. You are not just growing and planting seedlings any more. They are carbon sinks. Seedlings respond physiologically to light, nutrients, sun flecks, soils, and more. Even if all you did was pick up this book and read two pages a night, you would learn more than you ever thought possible. This is a great reference book, besides being an outstanding college text book.

Pocket Reference. T.J. Glover. 1996. 2nd Edition. Littleton, CO: Sequoia Publishing, Inc. 542 p. There are many versions of pocket reference books, and this is a superb example of one. Want to know the cement: sand:gravel ratio for high-strength floors? This book will have the answer, especially if you plan an addition to your greenhouse. A pound of water is 27.7 cubic inches. A gallon of water weighs 8.33 pounds. Such a book can really come in handy.

A Forest Journey: The Story of Wood and Civilization. J. Perlin. 1989, 2005. Woodstock, VT: The Countryman Press. 461 p. This is a must reading for all associated with the growing and planting of trees. This book, if you have not read it, should have quite an impact on you. Basically, humans have spent around 5,000 years deforesting this planet. The role that wood has played in the development of ancient and modern day civilizations is remarkable. This book rates as one of the 100 most important books that all humans should read in their lifetime. Here is an interesting quote concerning the use of wood in ancient Rome: "They calculated that the Roman villa's furnaces needed to burn about 286 pounds of wood per hour, or over two cords a day, to heat the building adequately." You should read what they burnt to keep a Roman bath hot! The Romans were not big on nurseries or reforestation.

Over the years I have built up quite a nice nursery-reforestation library by just letting people know I would cherish the books they gave me. Someone retires and wonders why anyone would care about a bunch of books written back in 1923 or 1948 or 1963. I happen to be one of those who care, because a lot of the older books have very good information in them. The problem with the exchange of information today is that the failures are not likely to be printed—we get only the success, without the other information that led to the success in the first place. Older documents often go into what did and did not work. It has long fascinated me how old our "new" ideas are. Probably one of the most useful aspects of our new references is that they grew out of older references. The older references have value because they teach present and future generations that (for instance) the concept of seedling physiological quality was known decades ago—not through some paper written in 1997.

I would be thrilled to have all of our TPN readers send in the citation(s) for their favorite reference books. What I have presented here is a mere tip of the iceberg. Do you have a favorite reference on greenhouse maintenance? What about propagation techniques? How about a fertilizer handbook or disease control manual? If you like a book a lot, then please send along a review of it and we'll try to print it.

Send your suggestions in, and I will print some of them in the next issue of *Tree Planters' Notes*. Keep reading and learning. More importantly, pass your knowledge and your books on to the next generation of growers and planters.

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