SECTION 8: Propagules

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8.0 PROPAGULES

Mixedwood Silviculture requires practitioners to integrate conifer and deciduous propagule deployment. This guide considers white spruce and aspen. White spruce propagule deployment options include seeding, planting and retention of advanced growth. At present, regeneration of aspen relies on suckering. Treatments that can improve the success of one species may have a negative impact on the other. Also, aspen establishment occurs within a short window (1-2 years post harvest) and, at present, there are no effective remedial treatments. This section discusses suckering of aspen (Section 8.1) and seeding and planting of white spruce (Sections 8.2 and 8.3).

Section 8.3 on planting of white spruce is drawn directly from *Ecophysiology of Northern Spruce Species: The Performance of Planted Seedlings* (Grossnickle 2000.). Sections included in the Silviculture Guide are only those considered critical by the authors of the Guide. The authors of the Guide recommend that practitioners obtain a copy of this book as it provides a comprehensive overview of the current understanding of spruce seedling performance in northern systems; it is obtainable from the NRC Research Press at the following link: http://pubs.nrc-cnrc.gc.ca/eng/books/books/9780660179599.html

Aspen–white spruce interactions and potential impacts of treatments are discussed in Sections 4, 5, and 7.

8.1 ASPEN SUCKERING IN MIXEDWOOD STANDS

In mixedwood silviculture, understanding the dynamics (and probability) of aspen establishment is critical to successful regeneration of mixedwood and deciduous stands – while it plays an equivocal role in white spruce regeneration acting as a commensal facilitator and a competitor. Thus, the probability of aspen regeneration potential gathered in the pre-harvest assessment is critical to setting objectives and determining establishment silvicultural regimes.

Aspen reproductive potential is driven by a combination of biotic, site, and abiotic factors. (The Deciduous Propagule Potential tool integrates several of these factors.) Potential for this species as a crop or competitive species is directly linked to its reproductive potential. Figure 8.1 offers a conceptual approach to identifying the factors that control aspen reproductive potential and the main causal agents underlying them.

The following are some suggested criteria for adequate establishment of aspen as a crop:

- Minimum stem density for successful polygon level of aspen is not clearly defined. Greene et al, 1999 suggest a minimum density of 35 stems per hectare in the unharvested stand. This density is based on several papers which found aspen suckering primarily occurred within 10 m of parent trees. Thus a single parent tree is capable of establishing aspen on approximately 300 m2. Approximately 35 parent trees are required to reforest a hectare. Others suggest at least 50 stems per hectare (see also Peterson and Peterson 1992, 1995, Frey et al. 2003); while Kabzems pers Comm. (2007) suggested approximately 80 stems per hectare.

- Even distribution of the stems across the proposed cutblock.
- Trees should be thrifty. If using the aspen thrift tool (incorporated into Deciduous Propagule Potential Tool), a minimum thrift rating of "Moderate".
- If using the Deciduous Propagule Potential Tool, a minimum rating of "Likely".

If an aspen stand (or the aspen component of a mixedwood stand) meets the preceding criteria, aspen regeneration potential is sufficient to meet mixedwood and possibly pure deciduous composition objectives via a leave-for-natural reforestation strategy. Note that site adjustment treatments may help overcome some of the reductions in aspen sucker potential associated with older stands (Fraser *et al.* 2003).

If a pure deciduous stand is desired after harvest, the silviculturist must pay particular attention to aspen vigor and distribution, as root suckers are the only reliable aspen propagule at present. Thus sufficient propagules, with abundant suckering potential, are critical to successful establishment of deciduous stands (Frey *et al*. 2003, Desrochers and Lieffers 2001).

If a mixedwood condition is the objective, aspen distribution is less critical than for pure deciduous stands, but a clumped distribution of ramets may lead to clumping of clones after harvest. For mixedwood objectives the vigor conditions outlined above remain critical.

Frey *et al.* (2003) provide an excellent review of the many external factors affecting aspen sucker regeneration. They summarize the current understanding of how the physiological phenomenon of suckering interacts with several environmental and operational factors. Silviculturists are advised to read this review as it provides a clear understanding of how operational practices and overall plant community status can impact aspen establishment.

There are several other potential impediments to aspen sucker regeneration. Identification of these impediments in the pre-harvest assessment provides the opportunity to prevent some of them, and to anticipate the need to address others via site adjustment. These factors include:

- Slope position and aspect. Mid-slope and southerly aspect are the most favourable; toe of slope and northerly aspects are the least favourable. Frey et al. (2003) suggest this phenomenon may be related to temperature regime.
- Presence of reedgrass competition in the developing stand. Reedgrass competes with aspen on several levels:
    - For nutrients. Reedgrass is a highly efficient scavenger for nitrogen (Comeau pers. Comm. 2006, Hangs et al. 2003, Landhäusser and Lieffers 1998).
    - Reedgrass thatch cools soil below the range (<12°C) best suited to aspen sucker development (Landhäusser and Lieffers 1998).
    - Reedgrass root and rhizome mass may physically impede root development of other species (Comeau pers. Comm. 2006).
- Waterlogging of aspen roots post-harvest can substantially reduce sucker number and vigour. At the pre-harvest assessment, potential for both waterlogging and compaction (which

exacerbates waterlogging) can be identified. Potential for waterlogging is driven by available moisture (sub-hygric or wetter moisture regime) and soil drainage class (impeded drainage is often associated with fine textured (clay or clay loam) soils.)

- Compaction. Traffic on sites when they are wet and the soil is not frozen can result in compaction of soil macropores (McNabb et al. 2001), which in turn can cause waterlogging and create physical barriers to aspen root penetration. Good management practice can prevent waterlogged or compacted soil through adjustment of harvesting practice.

Silviculturists should be alert for the risk factors identified above and address harvesting activities to ensure these risks do not occur, especially if a deciduous or mixedwood objective is desired.

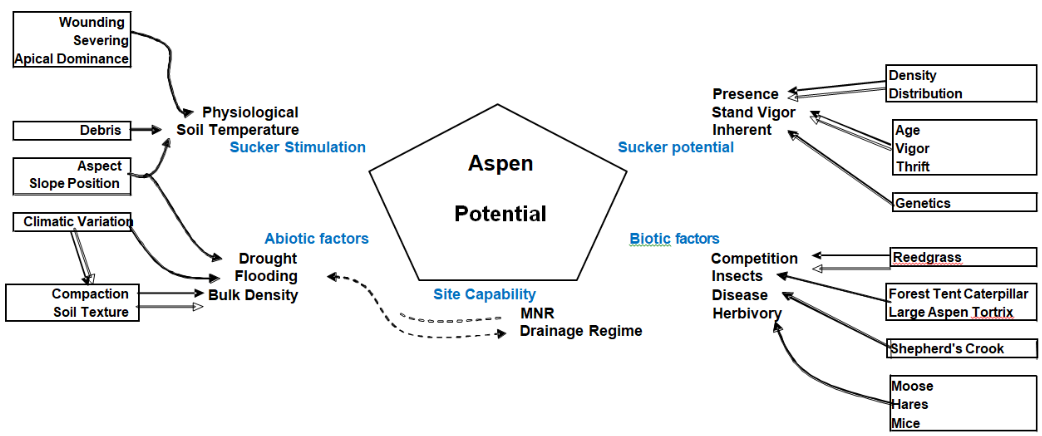


Figure 8.1. Aspen regeneration potential and causal factors (from Frey et al. 2003).

8.2 NATURAL AND ARTIFICIAL SEEDING IN MIXEDWOOD STANDS

The decision to use natural or artificial seeding to establish the conifer component is complex with many variables that must be considered. This guide considers seeding of white spruce.

8.2.1 SEED SOURCE AND DISPERSAL

Classified as an avoider species by Rowe (1983), white spruce can also be an invader if seed is available soon after disturbance. Niendstaedt and Zasada (1990) classify white spruce as mid-tolerant suggesting it has sufficient autecological plasticity to occupy both pioneer and mid-successional seral niches. This plasticity suggests white spruce may establish soon after disturbance or, depending on competition and seedbed conditions, linger under a rapidly establishing tree canopy (typically aspen or balsam poplar). White spruce seedlings established in the understory may persist until afforded an opportunity to enter the canopy as the pioneer deciduous tree canopy breaks up (Dix and Swan 1971, Lieffers *et al*. 1996, Green et al. 1999).

White spruce is a masting species and produces good seed crops at intervals of up to 15 years (Viereck and Schandelmeir 1980). Typically seed matures and falls in one year (Viereck and Schandelmeir 1980). However, seeds can remain viable for two years in cones and for one growing season once shed (Nienstaedt and Zasada 1990). Effective seed dispersal is about two tree heights (Viereck and Schandelmeir 1980) and is greater in the downwind direction (Stewart et al. 1998). Dispersal of 250-m or more is possible (depending on wind conditions); however, the bulk of seed falls within 20-m of parent trees. Although, the majority of white spruce seed production occurs in mast years there are years where light or local seed crops are produced resulting in ongoing white spruce reproduction (Nienstaedt and Zasada *ibid.*)

8.2.2 SEEDBED

Though able to germinate on forest litter (Ahlgren and Ahlgren 1981), recruitment of white spruce relies on the presence of suitable microsites (Place 1955, Simard et al. 1998, Prevost and Pothier 2003, Wang and Kemball 2005, Peters et al. 2004). In general, seedbed conditions decline with time since disturbance as duff depth, competition, and smothering by broadleaf litter increase (Korolef 1954, Greene et al. 1999, Simard et al. 2003). When conditions are open (i.e. after logging or fire) white spruce germination and short term survival can be improved by shading from deciduous species as they act to ameliorate moisture stress (Prevost and Pothier 2003, Wang and Kemball 2005). The benefits from shading are seen in the first few months following germination while the seedling develops roots through the duff into underlying mineral soil. Reaching mineral soil is critical to survival as mineral soil provides a more stable moisture supply than duff, thus reducing mortality due to heat and moisture stress (Rowe 1955, Waldron 1966). Simard et al. (2003) reported that, as a percentage of viable seeds sown, one year survival of artificially seeded white spruce under mature aspen and *Thuja occidentalis* (eastern white cedar) was approximately 3.9% on mineral soil, 4% on buried logs (level with the forest floor), 7.7% on unburied logs, and 1.5% on undisturbed forest floor litter. Similarly, measured two years after artificial seeding under a mature aspen canopy Wang and Kemball (2005) found white spruce recruitment to be 5.6%, 2.6%, 0.3% of viable seeds sown on exposed mineral soil, rotten logs, and undisturbed forest floor, respectively. It should be noted that despite higher germination and/or short term survival on decayed wood (i.e., rotten logs), seedlings are often visibly stressed (typically appearing chlorotic) and suffer from poor growth and survival.

8.2.3 GERMINATION, MORTALITY, AND SEED PREDATION.

Optimum moisture and temperature conditions for white spruce germination and establishment occur in the spring. Therefore, artificial seeding carried out in the spring before the dryer conditions of mid to late summer, increases the potential for seedling mortality. However, depending on leaf litter depth, seeding too early in the spring may result in seeds becoming suspended on compacted forest floor litter. If adequate heat and moisture is present the suspended seeds will germinate but soon die from desiccation. In a seven-year seeding trial of white spruce seeded annually under regenerating aspen (Kemball, Wang, and Westwood; Black River Fire project unpublished data) it was observed that desiccation, primarily due to failure of roots to establish contact with mineral soil or humus, followed by smothering from broadleaf litter, were the primary causes of early (i.e., first year) mortality. Seeding in the fall just prior to leaf drop, so that seeds can better contact suitable seedbed and take advantage of moist early spring conditions, is another option, particularly where litter accumulation will be modest (i.e., first few years post disturbance). Thin litter may improve success while thick litter is known to be detrimental (Waldron 1966, Koroleff 1954).

Seed predation can also be an important factor (Radvanyi 1970, Simard et al. 2003, Peters et al. 2004) to consider. Seed predator abundance (particularly small mammals) can vary significantly from year to year (see Peters et al. 2004, Moss and Boutin 2001). If using seed trees under a LFN seeding strategy both pre-dispersal cone predation (typically red squirrels, Peters et al. 2003) and post-dispersal predation (primarily mice and voles, Peters et al. 2004) must be considered. Unfortunately little quantitative information is available on seed predation for white spruce. In a recent study Peters et al. (2004) found a 30%–90% reduction in recruitment on unprotected plots vs. predator excluded plots.

8.2.4 SETTING REALISTIC GOALS

White spruce seeding, artificial or natural carries with it a much higher risk of failure than alternative regeneration tactics. The small size and delicate nature of recently germinated seedlings makes them highly susceptible to mortality from factors that have little or no impact on planted stock, e.g., moisture, seed predation, herbivory, smothering. However, trees established from seed are less susceptible to winter desiccation and frost heaving than planted trees, thus seeding may be a viable option if other conditions are favourable.

If artificial seeding is to be employed, distribution and density will be uncertain as germination and establishment of spruce depends on:

1. presence of suitable seedbed microsites,
2. moisture amount and duration,
3. predation,
4. smothering by broadleaf litter.

Distribution and density are even more uncertain if LFN is employed. Under a LFN seeding strategy the mast behaviour of white spruce must also be considered. In particular, Nienstaedt and Zasada make clear that a good mast year will inevitably be followed by a poor mast year. Preparing the seedbed by exposing mineral soil is the only sure way to improve success as other factors are largely stochastic and not amenable to amelioration. Furthermore, seedbed quality will erode substantially if there is a lag of more than a year or two between site preparation and occurrence of a mast year.

The use of artificial seeding may also be impacted by the availability and cost of seed. The practitioner should be aware of the seed zones, “ecological and genetic units which are intended to define areas of locally adapted tree populations” (Alberta Forest Genetic Resources Council), and regulations restricting movement of seed between zones.

Summary of requirements for successful white spruce establishment from seed:

- Adequate seed source
- Suitable seedbed microsites for germination and establishment
- Low competition

Summary of management considerations:

- High risk of failure
- Distribution and density will not be uniform (fill plant and or thinning may be required)
- Likely to require assertive control of competition
- Cost and availability of seed may be prohibitive

8.3 PLANTING SPRUCE IN NORTHERN FORESTS

This entire section of the Silviculture Guide is drawn directly from Ecophysiology *of Northern Spruce Species: The Performance of Planted Seedlings* (Grossnickle 2000) Please note that section and figure references in this section refer to numbers in the original book.

This section examines the influence of silvicultural practices on the physiological response and morphological development of spruce seedlings during the latter stages of development in the nursery and through early performance on reforestation sites. The forest regeneration process is complex because successful regeneration requires combining an understanding of physiological performance and morphological development characteristics of spruce species with proper silvicultural practices (Fig. 5). Ultimately, seedling performance on a reforestation site depends on the inherent growth potential of the seedling and the degree to which field site environmental conditions limit or enhance this potential.

Nursery cultural and preplanting silvicultural practices have a strong influence on spruce seedling performance immediately after planting. The effects of these practices on seedling performance need to be understood to make sound forest regeneration decisions (Fig. 5). Implicit within this preplanting program is the recognition of the inherent species characteristics when making the selection of the genetic seed source used for seedling production. Proper seed source selection ensures that seedlings are ecophysiologically suited to field site environmental conditions throughout the entire forest rotation (Section 4). Stock quality programs are an effective way of describing the performance potential of seedlings produced from various nursery cultural practices and determining the effects of preplanting silvicultural practices. The discussion starts at the point when final nursery cultural practices are applied to spruce seedlings and thus their implications on seedling field performance. Container-grown spruce seedlings are discussed in subsections on nursery culture effects, stock quality assessment, and stock type development in relation to seedling performance potential. Throughout the remainder of the discussion, information on both container-grown and bare-root spruce seedlings are utilized to examine the effects of preplanting and field site silvicultural practices. The discussion then continues through a logical sequence of operational events by examining storage and handling practices.

The reforestation site is a unique ecosystem, as a forested stand subjected to a disturbance such as harvesting alters the basic structure and function. The altered stand structure influences many processes of the future ecosystem and the microsite environment in which seedlings are to be planted (Section 1). This discussion examines the dynamics of the forest regeneration process within both clearcutting and partial forest canopy retention silvicultural systems. The intent is to try and define factors that can enhance as well as limit the development of spruce seedlings on reforestation sites.

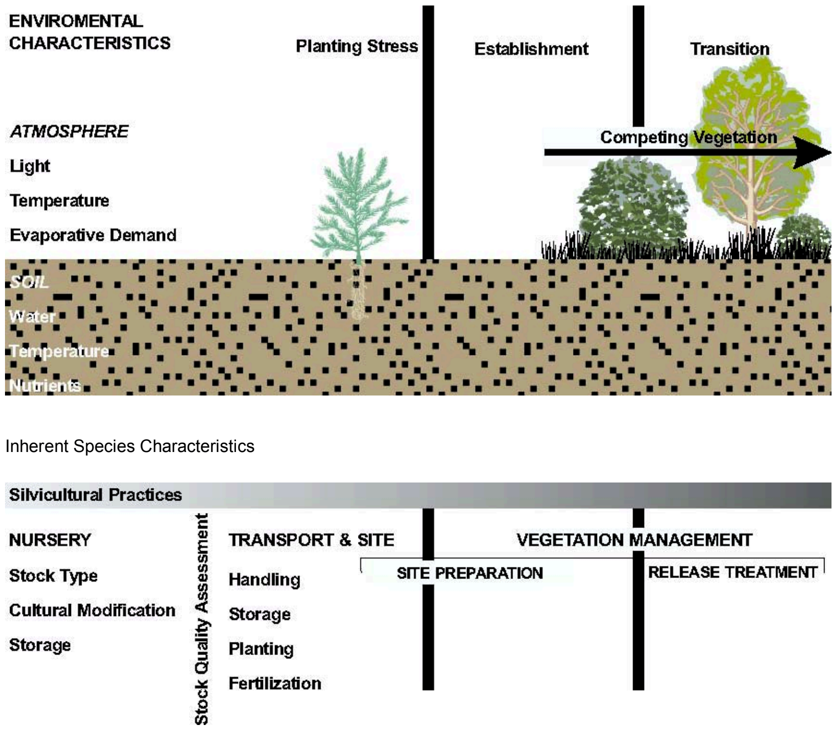


Fig. 5. A depiction of the forest regeneration process for spruce seedlings in response to site characteristics and silvicultural practices.

Newly planted spruce seedlings undergo a series of developmental phases (planting stress, establishment, and transition) on reforestation sites. The length of each phase is dependent upon the response of seedlings to site environmental conditions (Fig. 5). These phases may overlap, depending upon the development of seedlings and competing vegetation. These developmental phases are used to identify and examine each of the processes that can occur after spruce seedlings are planted on a reforestation site. Within each of these plantation development phases, spruce seedling performance is examined in relation to possible site limiting environmental conditions and silvicultural practices (e.g., site preparation, fertilization, and vegetation management) that can possibly mitigate these environmental constraints and improve seedling performance.

Spruce seedling physiological response during these plantation developmental phases determines survival and subsequent growth on reforestation sites. In addition, successful seedling development is affected by not only the past and future silvicultural practices, but also by current and future site environmental conditions (Fig. 5). These conditions continually change due to the development of competing vegetation. Further, vegetation management practices also contribute to plantation development in relation to competition from early successional species. Field performance of spruce seedlings is discussed in context with the interaction between competing vegetation and spruce seedlings during stand development on reforestation sites.

STOCK QUALITY ASSESSMENT

GENERAL CONCEPT

The study of stock quality assessment has evolved over the past 50 years. It is based on the need for a better understanding of performance capabilities for seedlings that are nursery-grown and out-planted on reforestation sites. Wakeley (1954) is usually recognized as the first person to identify the importance of morphological and physiological grading of seedlings prior to planting onto reforestation sites. Stock quality is now defined as the seedling's "fitness for purpose" (Lavender et al. 1980), as it relates to achieving specific silvicultural objectives. Clear and comprehensive stock quality information is necessary to make effective stock selection and field planting choices. In both North America and Europe, stock quality assessment programs are currently used by foresters to ensure quality control, enhance consumer confidence, avoid planting damaged stock, and improve nursery cultural practices (Dunsworth 1997). The following discussion examines both conceptual approaches and testing methods that can be used in conducting a stock quality assessment program.

Stock quality assessment has evolved to include both morphological and physiological tests (see reviews by Sutton 1979; Chavasse 1980; Jaramillo 1980; Schmidt-Vogt 1981; Ritchie 1984; Duryea 1985a; Glerum 1988; Lavender 1988; Puttonen 1989a; Hawkins and Binder 1990; Johnson and Cline 1991; Omi 1991; Mattsson 1997; Mohammed 1997; Puttonen 1997). The wide array of testing procedures now available has sometimes led to confusion in defining the specific purpose of stock quality assessment. Part of this confusion stems from the fact that stock quality assessment encompasses both nursery development (nursery growth phase, determination of lifting for storage, Section 5.1.3) and testing immediately before planting to determine probable field survival and (or) field performance (Duryea 1985b). With a clear definition of purpose for using specific testing techniques, nursery personnel and regeneration silviculturists can focus on obtaining specific information needed to make effective decisions. The following discussion is centered on the importance of assessing quality of planting stock immediately before out-planting to forecast field survival (Section 5.1.2.3) or field performance (Section 5.1.2.4). Due to the widespread use of root growth capacity as a stock quality procedure in reforestation programs, this testing approach is discussed in a separate section (Section 5.1.2.2).

When foresters consider using a stock quality program to assess their seedlings, a commonly expressed concern is how to select tests that are useful for providing information needed to make effective stock selection and field planting choices. A conceptual model has been developed to provide a means of understanding the importance of various testing procedures within a stock quality assessment program (Fig. 5.1.2.1). Determination of stock quality combines measurements of seedling properties that have been defined as material and performance attributes (Ritchie 1984). Material attributes are single-point measures of individual parameters that represent specific seedling subsystems (e.g., morphology, osmotic potential, root electrolyte leakage, nutrient content, individual gas exchange measurements). In contrast, performance attributes reflect an integrated effect of many material attributes, are environmentally sensitive seedling properties, and are measured under specific testing conditions (e.g., root growth capacity, freezing tolerance, 14-day gas exchange integrals). Both attribute types provide information on initial survival potential and field performance potential of seedlings. However, there is no guarantee that testing for initial survival potential provides information on field performance potential under limiting environmental conditions. Foresters need to define the specific silvicultural objectives they hope to achieve with a stock quality assessment program before selection of various testing procedures.

One testing approach that defines the quality of seedlings just prior to planting would be desirable. However, foresters must recognize that no single stock quality test is available for all seedling quality issues (Mattsson 1997; Puttonen 1997). Morphological parameters should not be used to solely assess stock quality, because seedling morphology does not describe the physiological vigor of seedlings (Mexal and Landis 1990). Also, stock quality assessment cannot be determined by individual seedling physiological parameters in isolation from other physiological attributes and morphological characterization (Lavender 1988). Proper stock quality assessment should be done with a combination of morphological and physiological attributes that provide the necessary information needed to make sound seedling-related forest regeneration decisions.

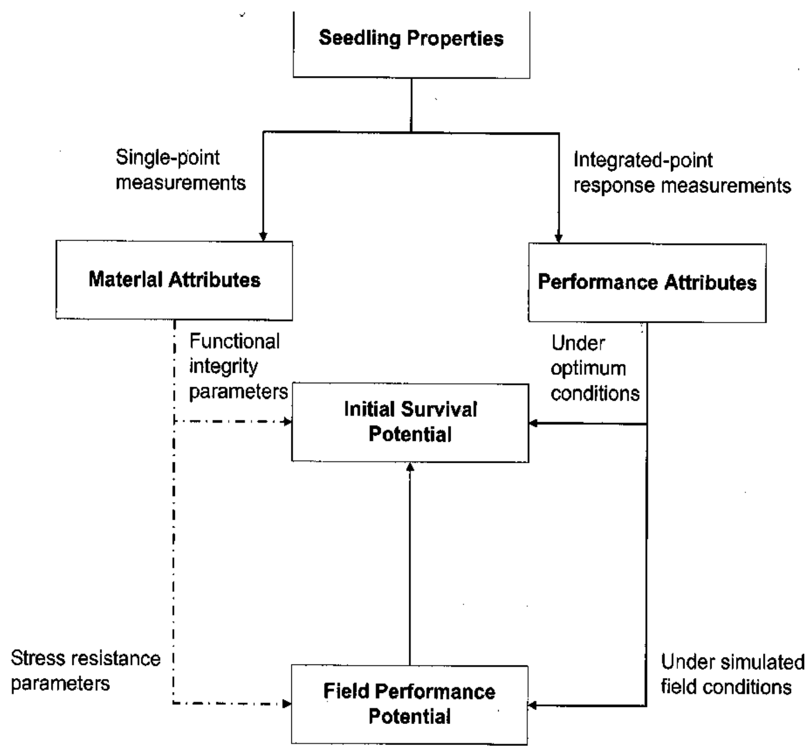


Fig. 5.1.2.1. A conceptual model of the relationship between material attributes, performance attributes, initial survival potential, and field performance potential in stock quality assessment (adapted from Folk and Grossnickle 1997).

ROOT GROWTH CAPACITY

Seedling root growth is the most common measurement tool used in operational programs throughout the world to define stock quality (Simpson and Ritchie 1997). This assessment approach is determined through a testing procedure called root growth capacity or root growth potential. The importance for a newly planted conifer seedling to grow roots has long been recognized (Wakeley 1954; Stone 1955). Numerous reviews have discussed the merits of measuring root growth within a stock quality assessment approach for determining seedling performance (e.g., Ritchie and Dunlap 1980; Ritchie 1985; Burdett 1987; Ritchie and Tanaka 1990; Sutton 1990).

Root growth capacity is the ability of seedlings to grow new roots under optimum environmental conditions (e.g., 20°C, 18-h photoperiod above a minimum of 25% full sunlight, with optimal soil water and fertility) over a prescribed length of time (e.g., from 7 to 14 days). The test is a quick visual assessment of seedling performance. The universality of root growth capacity in stock quality assessment programs throughout the world indicates the strength of this test to provide foresters with information they need to make seedling deployment decisions. The drawback of this stock quality assessment approach comes in the interpretation of the findings.

One misconception in interpreting results of root growth capacity testing is that root growth in spruce seedlings is constant over time. As previously discussed, root growth in spruce varies throughout the growing season (Fig. 2.6.2.1b). Due to the seasonal periodicity of root growth inherent within spruce species, healthy seedlings sometimes do not grow roots even under ideal environmental conditions (Section 3.9). Seasonal root growth capacity of interior spruce containerized seedlings, for the most part, follow the above-described seasonal pattern (Fig. 5.1.2.2a). In frozen-stored seedlings, root growth capacity remains high in storage if the seedlings are lifted and placed in storage when they have a high root growth capacity (Section 5.1.3). Immediately after seedlings are removed from storage, they retain a high root growth capacity which declines as seedlings begin shoot growth. The decline in root growth capacity continues during bud development and through the fall until dormancy intensity weakens. Thereafter, root growth capacity increases and remains high in storage. If seedling quality is based solely on root growth capacity, at certain times of the year false assumptions can be made that seedlings are of poor quality. It is recommended that a more comprehensive stock quality testing approach be considered, which provides not only an assessment of root growth capacity of seedlings but also an understanding of seedling stress tolerance and physiological response to potential reforestation site environmental conditions (Section 5.1.2.4). In this way, a measure of root growth capacity can then be placed in context with the overall quality of the seedlings.

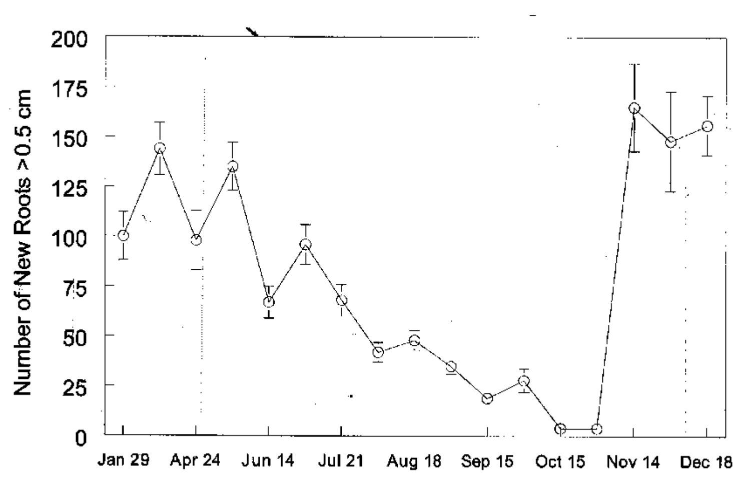


Fig. 5.1.2.2a. Seasonal pattern of root growth capacity (i.e., number of new roots) for container-grown interior spruce seedlings (N = 24: mean ± SE). Measurements recorded in December through April (i.e., outside of dashed lines) were taken on seedlings removed from frozen storage (Grossnickle, unreported data).

Another misconception in interpreting results of root growth capacity is that a single numerical scale is applicable for assessing root growth capacity under all operational conditions. Studies have found that root growth capacity changes because of the following parameters: species differences, genetic variation within a species, seedling size, and nursery cultural practice. For example, Engelmann spruce seedlings have lower root growth capacity than lodgepole pine seedlings grown under the same nursery cultural conditions (Ritchie et al. 1985). Root growth capacity has also been reported to vary between populations of black spruce seedlings raised under the same nursery cultural regime (Sutton 1983). This also occurs in interior spruce seedlings growing under the same nursery cultural regime and having a similar root system size (Fig. 5.1.2.2b). Root growth capacity of seedlings also changes with the size of the root system; greater new root growth occurs with a greater original root system size. Studies have shown that greater initial root mass is related to greater root growth capacity in pine (Johnsen et al. 1988; Williams et al. 1988) as well as in interior spruce (Grossnickle and Major 1994b) seedlings. Root growth capacity of spruce seedlings also varies, depending upon whether the stock type was grown and then stored for a spring planting program or fresh-lifted for a summer planting program (Fig. 5.1.2.2b). In addition, the root growth capacity of spruce seedlings varies, depending upon the cultural practices used by each nursery. Foresters must recognize that the capability of a seedling to grow roots can be influenced by many varying factors. As a result, it is difficult to standardize root growth capacity measurements taken under varying operational conditions.

A major problem with the use of root growth capacity for seedling quality assessment is the assumption that this test is an adequate approach for the prediction of survival and (or) growth of seedlings planted on reforestation sites (reviewed by Simpson and Ritchie 1997). There is a variable relationship between root growth capacity and field performance. Whether or not newly planted seedlings initially require new root growth for proper field performance is related to the planting stress phenomenon (Section 5.3). Briefly, planting stress occurs when a newly planted seedling has transpirational demands that exceed the ability of the root system to take up water from the soil system. One way planting stress is relieved is when root growth occurs and seedling water stress is reduced. Simpson and Ritchie (1997) believe that root growth capacity is strongly related to field performance when stock has an inherently low level of stress resistance and when site environmental conditions become more severe. These are conditions that lead to planting stress. However, if seedlings are not exposed to planting stress, then initial root growth is not essential for proper field performance. Simpson and Ritchie (1997) indicate that root growth capacity has no relationship to field performance when seedlings have an inherently high level of stress resistance and when site environmental conditions are mild.

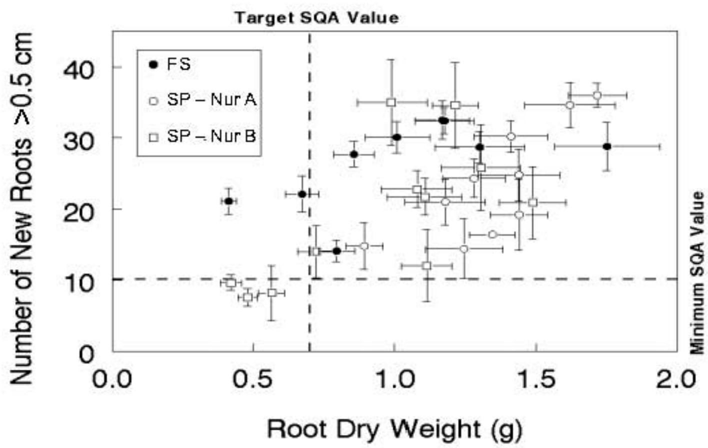


Fig. 5.1.2.2b. Relationship between root dry weight and the root growth capacity (determined over 14 days; N = 15–25: mean ± SE) for 30 clonal populations of container-grown (415-B) interior spruce seedlings. Clonal populations of seedlings came from a series of operational regeneration silvicultural practices: (i) spring-planted frozen-stored (FS), (ii) fresh-lifted for summer planting and grown at nursery A (SP – Nur A), or (iii) fresh-lifted for summer planting and grown at nursery B (SP – Nur B) (Grossnickle, unreported data). Minimum or target stock quality assessment (SQA) values are defined in Table 5.1.4.1.

What then does the measure of spruce root growth capacity provide to foresters as a stock quality measurement procedure? First, root growth capacity determines whether seedlings can grow roots within a defined time frame of the phenological cycle. Second, root growth capacity provides an indirect measure of the overall physiological condition of the seedling. If the seedling can grow roots, then all physiological processes that are required for root growth are functional. In other words, the testing approach is a measure of the functional integrity of the seedling, and it is a useful stock quality test that can determine seedling survival potential (Section 5.1.2.3). For example, if information is needed on seedling root growth under various limiting edaphic conditions (e.g., low soil temperature or low soil water, Table 5.1.4.1), root growth capacity testing procedures can be developed to assess performance in relation to these potential reforestation site environmental conditions (Section 5.1.2.4). Root growth capacity testing used in combination with an array of other stock quality testing procedures can provide information on the field performance potential of seedlings (Sections 5.1.2.4 and 5.1.4). Root growth capacity testing can provide foresters with an effective stock quality measurement procedure, but only when it is used with a proper understanding of its strengths and weaknesses.

SURVIVAL POTENTIAL TESTING

Initial survival potential is a measure of seedling "functional integrity." Functional integrity indicates whether stock is, or is not, damaged to the point of limiting primary physiological processes (Grossnickle and Folk 1993). The intent of these testing procedures are to remove seedlings that do not meet certain minimum physiological performance standards (i.e., the "bad apple concept"). Seedlings that meet minimum standards probably have a greater capability to survive in all but the most severe of field site environmental conditions (Sutton 1988). At present, there are a number of testing procedures that provide information on the initial survival potential of operationally produced stock. A number of these testing approaches are defined in Table 5.1.2.3. These types of tests measure seedling vitality under a specific set of conditions that define a certain level of quality when tested (Ritchie and Tanaka 1990; Langerud 1991). These tests have been developed for the purpose of batch-culling poorly grown and handled seedlings. They are used to categorize large groups of seedlings, all having a similar nursery cultural regime, or all from a similar seed source, by measuring a subsample from the entire population. Further specific information on each testing procedure can be found in the cited articles.

Measurement of seedling functional integrity helps determine the survival capability at the time of planting. An example of a testing program used to measure the initial survival potential of interior spruce is shown in Figs. 5.1.2.3a and 5.1.2.3b. In this example, spruce root systems were damaged to varying degrees just prior to stock quality testing. One day after exposure to damaging conditions, root systems were assessed for the degree of damage based upon the root electrolyte leakage procedure (greater root electrolyte leakage value means greater cell membrane damage, thus greater root damage). Seedlings were then grown under optimum environmental conditions and assessed at 1, 2, and 8 weeks by Pn and, root growth capacity, and survival testing approaches, respectively. Greater root damage resulted in seedlings having lower Pn and root growth capacity at 1 week, indicating that damaged root systems could not take up water, thus seedlings were under stress and Pn declined. Greater root damage also resulted in lower root growth capacity after a 2-week test. In addition, interior spruce seedlings with greater degrees of root damage had greater mortality (Fig. 5.1.2.3b). Thus, lower functional integrity can also indicate reduced survival potential.

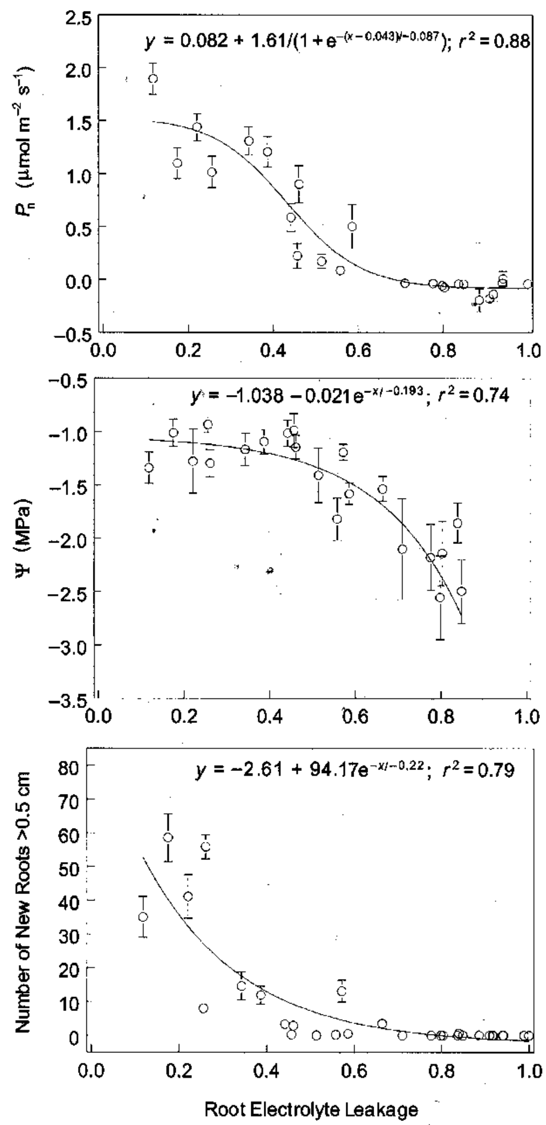


Fig. 5.1.2.3*a*. Stock quality assessment procedures to determine the initial survival potential of interior spruce seedlings with damaged root systems. Damage to the root system of seedlings (N = 8: mean ± SE) was determined by root electrolyte leakage (1 day after stress), net photosynthesis (Pn), shoot water potential () (1 week after stress), and root growth capacity (2 weeks after stress) (Grossnickle and Folk, unreported data). Seedlings were grown under optimum environmental conditions during the entire assessment period.

Table 5.1.2.3. Examples of stock quality tests that measure the initial survival potential of seedlings immediately before planting.

Stock quality tests	Test purpose	References
Root growth capacity (optimum environment)	A measure of seedling ability to regenerate new roots and an indirect measure of seedling physiological condition (Section 5.1.2.2).	Stone 1955; Ritchie and Dunlap 1980; Ritchie1985; Burdett 1987; Ritchie and Tanaka 1990; Sutton 1990; Simpson and Ritchie 1997
Vigor test	Expose seedlings to a stress event and then measure subsequent seedling survival.	McCreary and Duryea 1985, 1987; Lavender 1988
Shoot water potential	Measurement of Ψ as an in- direct measure of root sys- tem capability to absorb water.	McCreary and Duryea 1987; McKay and White 1997
Needle conductance, transpiration, or photosynthesis	Measurement of gas exchange as an indirect measure of root system capability to absorb water.	Örlander and Rosvall Ahnebrink 1987; Langerud et al. 1991
Infrared thermography	Measurement of needle temperature as an indirect measure of gas exchange and the root system capability to absorb water.	Weatherspoon and Laacke 1985; Örlander et al. 1989
Root System water loss capability	Measurement of root system water loss under positive pressure as an indirect measure of root system integrity.	Ritchie 1990
Fine root electrolyte leakage	Measurement of root electrolytes as an indirect measure of root system integrity.	McKay and Mason 1991; McKay 1992; Bigras and Calmé 1994; Bigras 1997; McKay and White 1997; McKay 1998
Enzymatic activity	Determination of whether cell tissue is damaged or dead.	Lindström and Nyström 1987; Puttonen 1989b
Chlorophyll fluorescence	Direct measure of photosynthetic capacity and an indirect measure of seedling overall quality.	Vidaver et al. 1989, 1991; Binder et al. 1997
Stress-induced volatile emissions	A measure of anaerobic respiration due to cell injury.	Hawkins and DeYoe 1992; Templeton and Colombo 1995

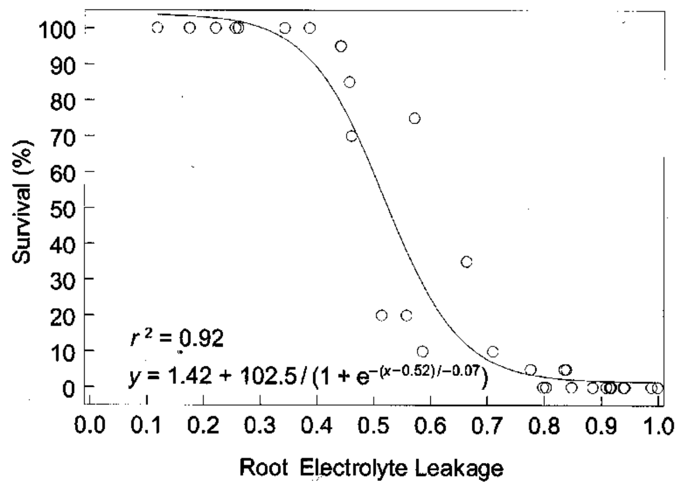


Fig. 5.1.2.3b. Stock quality assessment of interior spruce seedlings with damaged root systems measured by root electrolyte leakage (1 day after stress) (subpopulation of N = 8) and survival (N = 25) (8 weeks after stress) (Grossnickle and Folk, unreported data). Seedlings were grown under optimum environmental conditions during the entire assessment period.

This example demonstrates that stock quality assessment tests are capable of measuring the functional integrity of interior spruce seedling root systems suspected of being exposed to damaging conditions. Very rapid testing procedures, such as root electrolyte leakage, chlorophyll fluorescence, and stress-induced volatile emissions, have the ability to forecast seedling performance for up to 8 weeks after exposure to a damaging event. If there is suspected damage to the shoot system, material attributes that measure gas exchange or photochemical processes are best suited to quickly detect the functional integrity of the shoot system (Table 5.1.2.3). Further testing of performance attributes (e.g., root growth capacity) is required if material attribute testing detects shoot damage.

Seedlings that have reduced functional integrity can have poor field survival. As shown in Figs. 5.1.2.3a and 5.1.2.3b, spruce seedlings that cannot grow roots have a low survival capability. This same phenomenon can occur in spruce seedlings that are planted on reforestation sites; low root growth capacity results in low field survival (Fig. 5.1.2.3c). In fact, this trend was still evident for the survival of interior spruce seedlings after 5 years (Simpson and Vyse 1995).

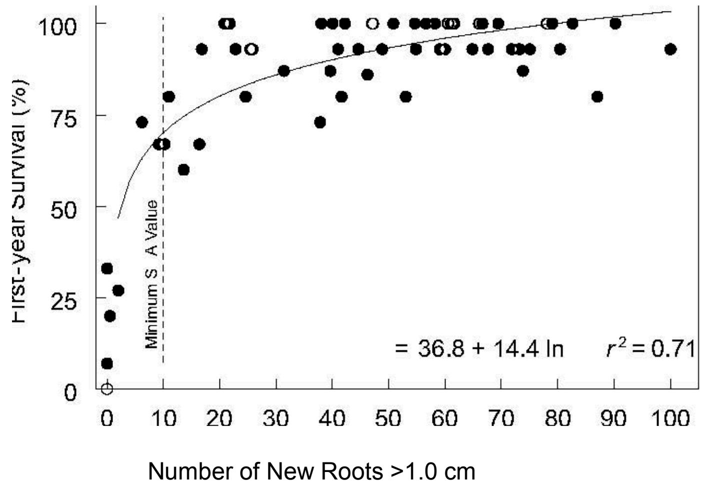


Fig. 5.1.2.3c. The relationship between first-year survival on a reforestation site and the capability of interior spruce seedlings to grow roots at the time of planting. Each point represents mean survival and mean root growth capacity of five seedlings taken from the same sample population (adapted from Simpson 1990).

Measuring root growth capacity can predict field survival when seedlings have low to average stress resistance and when seedlings are planted on sites with limiting environmental conditions (Simpson and Ritchie 1997). This rationale has led to the conclusion that both bare-root (Burdett and Simpson 1984) and container-grown (Simpson et al. 1988) spruce seedlings have a natural root growth capacity threshold of an average of 10 new roots (>1.0 cm in length) per plant, which is used as a batch culling guideline in British Columbia. Spruce seedlings with low root growth capacity (<10 new roots) have the potential for poor survival, which results in a greater chance of plantation failure. This guideline has provided a means for defining the risk of planting seedlings on reforestation sites that do not meet this minimum root growth capacity standard. The capability of a spruce seedling to grow roots can be influenced by many varying factors (Section 5.1.2.2). Thus, caution should be used in assuming that a standardized root growth capacity guideline, taken under varying operational conditions, is always representative of the functional integrity of the seedlings.

PERFORMANCE POTENTIAL TESTING

Seedling performance on a reforestation site depends on inherent growth potential of the seedling and the degree to which field site environmental conditions limit or enhance this potential. Thus, the degree to which seedlings are suited to site conditions has the greatest influence on seedling performance immediately after planting (Burdett 1983). Seedling characteristics that accurately determine field growth are needed to define the intrinsic performance potential of planting stock to site conditions (Sutton 1982, 1988). As a result, seedling performance potential should be characterized in relation to anticipated field site environmental conditions (Duryea 1985b; Sutton 1988; Puttonen 1989a; Grossnickle et al. 1988, 1991a, 1991b; Hawkins and Binder 1990) (Fig. 5.1.2.1). In addition, an array of morphological and physiological tests that examine factors important for determining seedling field performance potential is required because stock quality reflects the expression of a multitude of physiological and morphological attributes (Ritchie 1984; Grossnickle et al. 1991a, 1991b). A program that measures seedling response to simulated primary planting site environmental conditions can provide information on field performance potential (Grossnickle et al. 1991a, 1991b; Folk and Grossnickle 1997). Thus, field performance potential testing is a measure of seedling physiological stress resistance capability. This testing approach describes how seedlings physiologically respond to potential reforestation site environmental conditions.

Based on stress tolerance and avoidance concepts defined by Levitt (1980), performance potential tests have been developed to measure seedlings physiological response and morphological development under a range of environmental conditions. Examples of tests that can be used to assess field performance potential are shown in Table 5.1.2.4. Seedlings are normally exposed to some type of stress after planting on a reforestation site (Sections 5.3 and 5.4). As a result, stock quality tests conducted in a defined stress environment have a higher capability to forecast field performance potential. In developing test environments, predominant environmental conditions that seedlings are normally exposed to in the field need to be defined. Test environments should be developed to match the range and combination of anticipated environmental conditions seedlings can be exposed to just after planting on the reforestation site. The anticipated environmental conditions can be defined by silviculturists during on-site development of regeneration prescriptions.

It is necessary to test a combination of attributes in order to develop a comprehensive picture of seedling performance potential. Field performance potential is determined by material attributes that measure or define stress tolerance, avoidance, or resistance and by performance attributes under simulated site environmental conditions (Grossnickle et al. 1991a, 1991b; Folk and Grossnickle 1997). Figure 5.1.2.4a provides examples of field performance potential testing programs that can be applied to seedlings slated to be planted on field sites with anticipated cold or drought environmental conditions. Attribute selection varies, depending upon both the anticipated field site environmental conditions and the defined needs of the end-user. Testing for field performance potential is designed to allow the user to obtain information on stock to meet a defined purpose. This testing program usually falls into one of two categories.

First, field performance potential assessment can be measured on healthy seedlings to define field performance potential in relation to optimum, as well as possible, limiting field site conditions. An example of this stock quality assessment procedure is presented in Section 5.1.4 to describe interior spruce containerized stock types used in spring and summer planting programs and for container-grown seedlings of various sizes.

Second, field performance potential assessment can be determined on seedlings with minor damage where performance and survival is limited under stressful conditions, but not under optimal environmental conditions. An example of this stock quality assessment procedure follows.

Measuring field performance potential of seedlings with minor damage helps determine whether field performance is limited at the time of planting. An example of a testing program to measure the initial field performance potential of spruce is shown in Fig. 5.1.2.4b. These container-grown interior spruce seedlings, destined for a summer planting program, were originally grown under optimum conditions in a greenhouse during early spring. The seedlings were then moved into an outdoor compound where they were inadvertently exposed to stressful atmospheric conditions (i.e., high VPD and light) during the late spring. Although the seedlings were kept well watered, the needles developed sun-scald, or a bleaching of the upper surface of the needles. Seedlings from across the full range of sun-scald conditions were capable of growing roots (all seedlings grew >80 new roots) under the optimum environmental conditions of a standard root growth capacity test. Seedlings were also tested to determine whether the needle sun-scald would affect drought avoidance capability. Both a material attribute test (cuticular transpiration) and a performance attribute test (change in Ψunder drought) indicated that sun-scalded seedlings lacked adequate drought avoidance capability. These sun-scalded interior spruce seedlings had damaged needles that would have limited their performance and survival under drought on a reforestation site. This type of information on seedling quality could only have been determined with the use of performance testing designed to assess drought avoidance capability.

CAUTIONS IN APPLYING STOCK QUALITY RESULTS

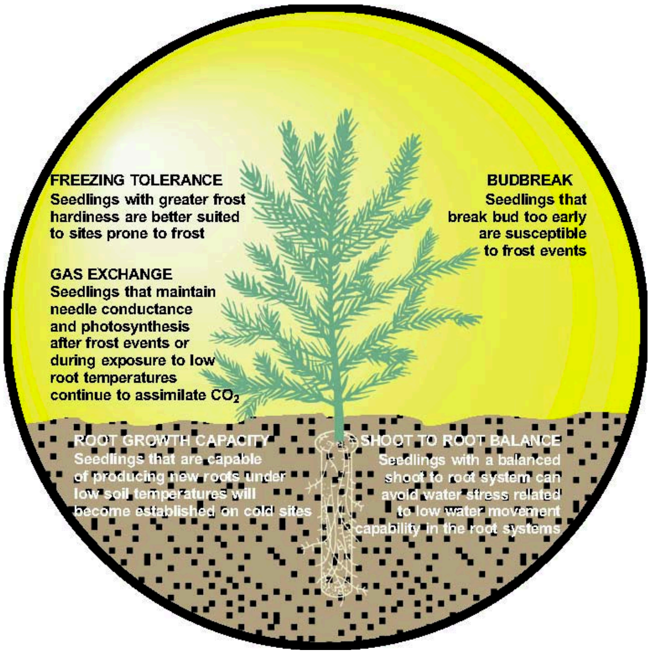
Limitations are inherent in stock quality assessment, depending on time of testing and the seedling morphological and physiological attributes that are measured (Puttonen 1989a, 1997). These limitations influence test result usage. To define field performance, morphological and physiological attributes need to be tested just prior to field establishment. This provides information on seedling initial field performance capability. However, spruce seedling inherent stress resistance changes as seedlings grow and follow the normal seasonal phenological cycle (Section 3.9). These patterns of stress resistance also change as seedlings are exposed to field site environmental conditions. Any testing procedure is just a “snapshot” of a single point in time along this seasonal pattern, making it difficult to accurately forecast all future seasonal patterns. Thus, the capability of these stock quality measurements to forecast seedling field performance potential is limited to a time frame that spans into the first growing season on a reforestation site.

Table 5.1.2.4. Examples of material and performance attributes used for stock quality testing and their intended purpose for defining field performance potential.

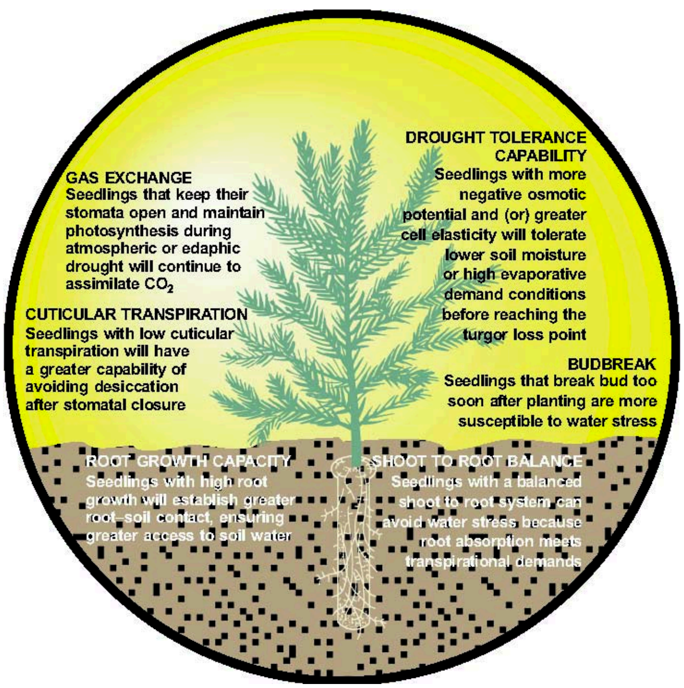
Attribute	Test purpose	References
Material attributes		
Height	General measure of Pn capacity and transpirational area; advantage on sites with brush competition; reflection of potential height growth.	Armson and Sadreika 1979; Cleary et al. 1978; Mexal and Landis 1990
Diameter	General measure of seedling durability, root system size, and protection from drought and heat damage.	Cleary et al. 1978; Mexal and Landis1990
Height to diameter ratio	General measure of shoot sturdiness.	Mexal and Landis 1990
Root dry weight	Indicator of root absorptive surface.	Thompson 1985
Shoot to root ratio	Measure of seedling drought avoidance potential.	Thompson 1985
Bud length, bud volume, needle primordia	General measure of predetermined shoot extension.	Kozlowski et al. 1973; Colombo 1986
Number of branches and buds	Indicator of seedling growth potential.	Grossnickle et al. 1991a
Osmotic potential at turgor loss point (Ψ tlp)	Quantitative measure of drought tolerance.	Tyree and Jarvis 1982
Cuticular transpiration	Ability of needles to avoid water loss after stomata have closed.	Vanhinsberg and Colombo 1990
Mineral nutrient status	Indicator of general seedling health and growth potential.	Ingestad 1979; Timmer 1997; Section 5.4.6.1
Carbohydrate reserves	Indicator of general seedling health and growth potential.	Marshall 1985
Days to terminal budbreak	Measure of bud dormancy and indirect measure of changes in drought and freezing tolerance.	Lavender 1985; Burr 1990

Table 5.1.2.4 (concluded).

Attribute	Test purpose	References
Performance attributes		
Root growth capacity	General indicator that all systems in a seedling are functioning properly and a measure of seedling performance potential (Section 5.1.2.2).	Ritchie 1984; Burdett 1987
Root growth capacity at low root temperature or after drought	Measure of seedling performance potential under limiting edaphic conditions.	Ritchie 1985; Grossnickle et al. 1991a
Freezing tolerance	Measure of seedling tolerance to freezing temperatures.	Glerum 1985
Pn over optimum conditions (14-day)	Measure of seedling photosynthetic capacity.	Grossnickle et al. 1991a
Pn over low root temperature conditions (14day)	Measure of seedling tolerance to cold soils.	Grossnickle et al. 1991a
Pn after drought	Measure of seedling drought tolerance in response to a defined level of water stress.	Grossnickle et al. 1991a



Cold Stresses



Drought Stresses

Fig. 5.1.2.4a. Possible stock quality testing procedures for determining spruce seedling field performance potential in response to either cold or drought reforestation site environmental conditions.

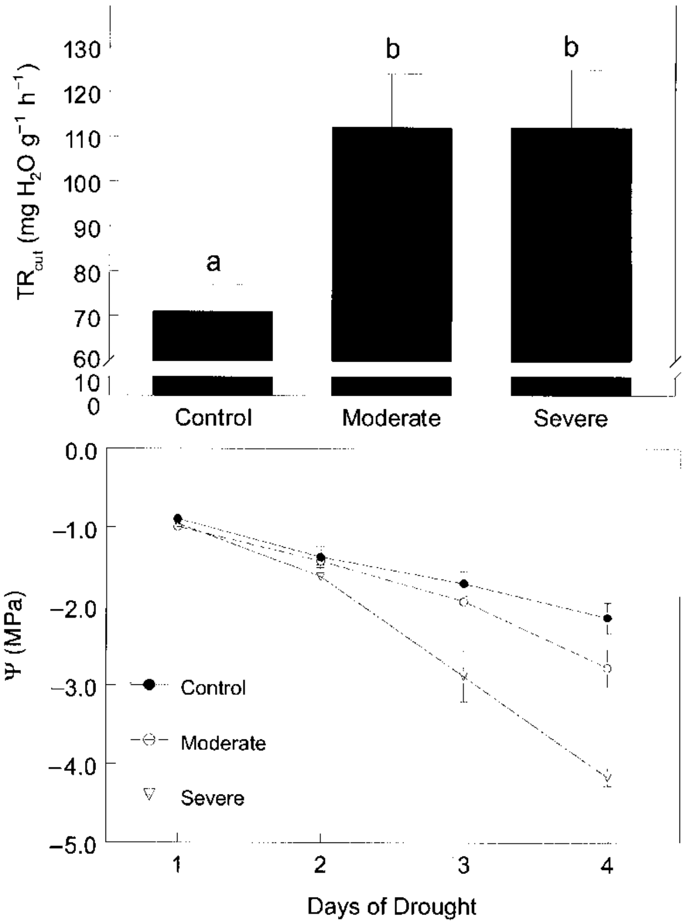


Fig. 5.1.2.4b. Stock quality assessment of interior spruce seedlings with varying degrees of needle sun-scald (i.e., moderate and severe) measured by performance potential testing under drought (material attribute: cuticular transpiration (TR_{cut}) (N = 6: mean + SE); performance attribute: change in shoot water potential (Ψ) under drought (N = 8: mean ± SE)). Letters on the bar graph represent whether seedlings from different damage categories were significantly different as determined by an ANOVA and Tukey's mean separation test (p = 0.05) (Grossnickle and Folk, unreported data).

When conducting any type of stock quality assessment procedure, one must recognize that differences in test results can occur due to species, genetic variation of seedlots (Section 4), variability in nursery culture, storage regimes, time of planting, and variability in testing conditions. Separate testing standards need to be developed for seedlings produced from various combinations of seedlot selections and nursery cultural decisions. Seedling users also have to be aware that the mishandling of stock during transport to planting sites, improper planting procedures, and unpredictability of field site environmental conditions can all influence how test results conducted prior to field planting match up with initial seedling survival and (or) field performance. Results derived from stock quality testing are only as good as the quality of operational procedures used in the overall forest regeneration program.

CONTAINER-GROWN STOCK TYPE CHARACTERIZATION

Northern spruce species are produced as both container-grown and bare-root stock types throughout the world. By the early 1990s, over 90% of the conifer seedling production in British Columbia and over 75% of all conifer seedlings in Canada were produced as container-grown seedlings (Arnott 1992). This section focuses on the range of both physiological and morphological attributes of spruce stock types currently being produced for planting in British Columbia. The intent is to give readers an appreciation of what can be created within a containerized nursery program growing spruce seedlings.

The Styroblock® container system was developed during the 1970s and is currently the most popular container system used to grow conifer seedlings in British Columbia (Arnott 1992). Stock type characterization of spruce seedlings described in this section primarily pertains to container-grown seedlings produced within this Styroblock® container system. Section 5.1.4.1 addresses the performance of spring-planted versus summer-planted stock types, while Section 5.1.4.2 examines the performance characteristics of different size stock types. The initial performance of spruce seedlings in the field is related to their stock type. Performance is dependent upon the inherent growth potential of a stock type and can be defined by performance potential testing within a stock quality assessment program (Section 5.1.2.4). The following sections describe the stock quality attributes of currently produced stock types.

Containerized spruce seedlings can also be produced through the vegetative propagation systems of rooted cuttings and somatic embryogenesis tissue culture. These vegetative propagation technologies provide the opportunity to capture the additional genetic gains produced by tree improvement programs and can be used for bulking up the most elite, full-sib families. Section 5.4.1.3 briefly discusses the current developments of these propagation technologies for spruce forest regeneration programs.

SPRING-VERSUS SUMMER-PLANTED SEEDLINGS

This section provides a representation of performance potential attributes inherent in spruce containerized stock types commonly used during the spring and summer planting seasons. The performance of stock types used in the spring and summer planting program are also examined, in a later section, over two growing seasons in order to define how they become established on reforestation sites (Section 5.4.1.3). Stock types have their greatest effect on performance as seedlings become established and start to grow on the reforestation site. Each stock type has a specific growth pattern and level of stress resistance which affect physiological response and morphological development on a reforestation site. Spring-planted seedlings develop both the shoot and root systems during the first growing season. In contrast, summer-planted seedlings only develop root systems during the first growing season; these seedlings' first shoots elongate during the second growing season.

Morphological characterization of containerized stock types provides insight into the balance of a seedling. The 2+0 stock type has an overall larger shoot system than the other stock types due to the additional period of time for development in the nursery (Table 5.1.4.1). All stock types have morphological balance of their shoots (i.e., height to diameter ratio) as well as between their shoot and root. The 2+0 seedlings intended for the summer planting program have a larger shoot to root ratio, which is reflective of a larger shoot system development over two growing seasons. Root system development was comparable between all of the stock types, indicating that container cavity size limited continued root development during the second nursery growing season. Both 1+0 stock types have a similar number of lateral branches, although seedlings slated for summer planting have ~50% more buds along the shoots, compared to seedlings used in spring planting. The 2+0 stock type has fewer lateral branches than both 1+0 stock types, although it has a number of buds along the shoots comparable to the 1+0 summer-planted stock type. The number of needle primordia found in the terminal bud of both 1+0 and 2+0 stock types ranged from 186 to 250. These buds are the sites for potential shoot growth after seedlings are planted. However, seedlings planted in the summer do not usually break bud, and thus they have no shoot growth during the first field season, while seedlings planted in the spring usually break bud after a period of 10–14 days.

Root growth depends upon the edaphic conditions of the testing procedure. In this example, all stock types have comparable ability to grow roots under optimum conditions (Table 5.1.4.1). Spring-planted seedlings can show a wide range in root growth capacity, and this may be related to lifting and storage practices (Section 5.1.3). In contrast, root growth capacity of summer-planted seedlings seems fairly comparable between years (Fig. 5.1.1.1) and stock types. When spring-planted seedlings are planted under low soil temperature, root growth is reduced (Table 5.1.4.1) (Section 3.5.1). This indicates that even seedlings with acceptable root growth capacity can have difficulty becoming established when soil temperatures are low in the spring (Section 1.2.1). Summer-planted seedlings show good root growth after drought stress and can develop an effective root system to ensure establishment of seedlings (Table 5.1.4.1). This is an important attribute for summer-planted seedlings.

Seedlings planted in the spring (usually around mid May) have a high level of stress resistance just after planting. This is reflected in high freezing tolerance, drought tolerance, and drought avoidance characterization (Table 5.1.4.1). As these seedlings break bud, stress resistance declines, and 4 weeks after planting (during late spring and early summer), seedlings are at a low level of stress resistance and are in their most rapid phase of shoot growth. This development pattern conforms with the typical seasonal cycle for spruce seedlings (Section 3.9) and is the period when there is the lowest potential for frost (Section 1.2.3) or drought on northern reforestation sites.

Seedlings planted in the summer (usually around mid July) have low stress resistance just after planting. Low levels of freezing tolerance, drought tolerance, and drought avoidance are typical of both 1+0 and 2+0 stock types (Table 5.1.4.1). Thus, these seedlings are potentially vulnerable to freezing or drought just after planting. The only attribute that varies between these stock types is that 2+0 seedlings have lower cuticular transpiration than 1+0 seedlings, which provides greater drought avoidance capability under field conditions when VPD is high (Section 1.3.2). After 4 weeks, summer-planted seedlings show an increase in freezing tolerance, drought tolerance, and drought avoidance. Summer-planted seedlings do not break bud during the first growing season, and the development of stress resistance is reflective of the normal late-summer development in spruce seedlings (Section 3.9).

Spruce seedlings coming out of storage usually have low gas exchange capacity (Section 5.1.3). This pattern is reflected in the lower P_n of spring, compared to summer, planted interior spruce seedlings (Table 5.1.4.1). Spring-planted seedlings have reduced gas exchange capacity (i.e., P_n

reduced by 23%) under low root temperature, which is normal phenomenon for spruce seedlings (Section 3.5.1). Summer-planted seedlings have higher P_n than spring-planted seedlings, which is reflective of the high level of gas exchange capacity found during the summer (Section 3.9). Interestingly, the 1+0, compared to 2+0, summer-planted stock type has higher P_n. After drought, summer-planted seedlings have a 40–55% decrease in P_n, with this reduction in P_n reflective of the low drought tolerance, thus P_n recovery (Section 3.5.2.1). As with root growth, the response of P_n is sensitive to field edaphic conditions, which can limit the gas exchange of seedlings just after planting.

Spring-and summer-planted stock types have different growth patterns and levels of stress resistance at the time of planting, which affects their physiological response and morphological development. It also needs to be realized that the level of stress resistance changes quite rapidly within a month after seedlings are planted. Data presented for these interior spruce stock types are intended to represent the general trends in inherent performance capabilities. Absolute values for any individual attribute can change from year to year, depending upon nursery cultural practices (Section 5.1.1) and the genetic source (Section 4). Nevertheless, these general differences in field performance potential should be recognized when making stock type selections. This information should be used in conjunction with knowledge of the reforestation site environment to select the best stock type and timing for planting.

Table 5.1.4.1. Stock type characterization (N = 10–24, depending on test: mean ± SE) of interior spruce seedlings used in spring and summer planting programs in British Columbia. Characterization is based upon stock quality attributes for 1+0 seedlings grown in 415B (at 105 mL) containers and for 2+0 seedlings grown in 415D (at 170 mL) containers (Grossnickle and Folk, unreported data).

	Spring-planted seedling		Summer-planted seedling		
	Units of value		Units of value		
Attribute[a]	1+0	Comments	1+0	2+0	Comments
Height	23.2 ± 2.1 cm	Above BCMoF target of 22.0[b]	24.8 ± 0.9 cm	28.0 ± 1.4 cm	BCMoF target of 22.0 for 1+0 and target of 30 for 2+0[b]
Diameter	3.5 ± 0.3 mm	At BCMoF target of 3.5[b]	3.6 ± 0.3 mm	4.7 ± 0.2 mm	BCMoF target of 3.5 for 1+0 and above the minimum of 4.2 for 2+0[b]
Height to diameter ratio	6.5 ± 0.3 cm mm^{-1}	Fits the accepted BCMoF target[b]	6.9 ± 0.1 cm mm^{-1}	6.2 ± 0.3 cm mm^{-1}	Fits the accepted BCMoF target[b]
Shoot dry weight	2.72 ± 0.3 g	—	2.3 ± 0.2 g	3.3 ± 0.2 g	—
Root dry weight	1.07 ± 0.12 g	Exceeds the accepted BCMoF target of 0.7 g[b]	0.72 ± 0.1 g	1.0 ± 0.2 g	Fits the accepted BCMoF target of 0.7 g[b]
Shoot to root ratio	2.9 ± 0.3 g	Good balance for drought avoidance[c]	2.9 ± 0.2 g	3.5 ± 0.2 g	Good balance for drought avoidance[c]
Number of branches	16 ± 1	Large number of branches	17 ± 1	10 ± 1	Large number of branches
Number of buds	23 ± 1	Sites for potential shoot growth	36 ± 3	34 ± 2	Sites for potential shoot growth
Needle primordia in the terminal bud	230 ± 20	High predetermined shoot growth potential	186 ± 12	251 ± 24	Good predetermined shoot growth potential
Budbreak	10–14 days after planting	Influences subsequent physiological response	Not until the next spring	Not until the next spring	Influences subsequent physiological response

Table 5.1.4.1 (*continued*).

Attribute[a]	Spring-planted seedling: Units of value 1+0	Spring-planted seedling: Comments	Summer-planted seedling: Units of value 1+0	Summer-planted seedling: Units of value 2+0	Summer-planted seedling: Comments
Root growth capacity, optimum	32.2 ± 4.1	Fits the accepted BCMoF target[d]	40.5 ± 3.2	31.3 ± 3.6	Fits the accepted BCMoF target[d]
Root growth capacity, low temperature (10°C)	1.2 ± 0.5	5% of optimum RGC	—	—	—
Root growth capacity, after drought (–2.5 MPa)	—	—	28.2 ± 2.3	23.0 ± 7.1	70% of optimum RGC
Freezing tolerance at planting (II[e] at –6°C)	11 ± 5%	Freezing tolerance 4 weeks after planting: 44 ± 8%	45 ± 4%	43 ± 5%	Freezing tolerance 4 weeks after planting: 18–13 ± 1% for both stock types
Drought tolerance (Ψ_{tlp})	–2.17 ± 0.24 MPa	Drought tolerance 4 weeks after planting: –1.48 ± 0.21 MPa	–1.6 ± 0.17 MPa	–1.6 ± 0.15 MPa	Drought tolerance 4 weeks after planting: –2.02 ± 0.22 MPa for the 1+0 stock type
Drought avoidance cuticular transpiration	0.41 + 0.08 mg $cm^{-2}\ s^{-1}$	Increases to 0.82 ± 0.06 mg $cm^{-2}\ s^{-1}$ after 4 weeks	0.92 + 0.12 mg $cm^{-2}\ s^{-1}$	0.61 + 0.12 mg $cm^{-2}\ s^{-1}$	Decreases to 0.66 ± 0.06 mg $cm^{-2}\ s^{-1}$ after 4 weeks for the 1+0 stock type
P_n optimum (14-day avg.)	1.37 + 0.12 µmol $m^{-2}\ s^{-1}$	At 45% of summer-planted seedling	2.98 + 0.37 µmol $m^{-2}\ s^{-1}$	2.42 + 0.27 µmol $m^{-2}\ s^{-1}$	Comparable to actively growing seedlings at a similar light level

Table 5.1.4.1 (*concluded*).

	Spring-planted seedling		Summer-planted seedling		
	Units of value		Units of value		
Attribute[a]	1+0	Comments	1+0	2+0	Comments
P_n at low root temperature (10°C) (14-day avg.)	1.06 + 0.28 µmol m^{-2} s^{-1}	Drops to 77% of optimum	—	—	—
P_n after drought (–2.5 MPa)	—	—	1.62 + 0.24 µmol m^{-2} s^{-1}	1.08 + 0.37 µmol m^{-2} s^{-1}	Drops to between 45 and 60% of optimum, for both stock types, during recovery

[a] Description of attributes are found in Table 5.1.2.4.
[b] Scagel et al. 1993; BCMoF, British Columbia Ministry of Forests.
[c] Grossnickle and Major 1994*b*.
[d] Section 5.1.2.2.
[e] Index of freezing injury.

SEEDLINGS OF VARIOUS SIZES

Foresters are frequently confronted with the fact that on some reforestation sites, vegetation can shade newly planted seedlings, thus reducing field performance (Section 5.5). Another problem facing foresters is that field sites with limiting environmental conditions may restrict the performance of planting stock. A solution being considered to deal with these regeneration problems is the use of larger planting stock. It is assumed that larger planting stock has the inherent performance potential to compete with other vegetation and has greater stress resistance to handle environmentally limiting field site conditions. This section provides information on the performance potential attributes inherent in spruce containerized stock types that have a range in sizes commonly used during the summer planting season. Stock quality characterization just before planting describes the material and performance attributes defined in the stock quality assessment section (Section 5.1.2). The field performance for spruce seedlings of various sizes under reforestation sites conditions is described elsewhere (Section 5.4.1.4).

Morphological characterization provides information on the shoot and root structural differences between these stock types. Seedlings grown in large-volume container cavities have greater shoot and root size, but maintain a comparable balance within the shoot system (i.e., similar height to diameter ratios), and between the shoot and root system (i.e., similar shoot to root ratios) (Table 5.1.4.2). Other work has found that spruce seedlings grown in large-volume container cavities are taller, have larger root collar diameters, and greater total shoot and root dry weights (Lamhamedi et al. 1997; Paterson 1997). In addition to having a taller shoot, seedlings grown in large-volume container cavities have a greater number of branches and buds, but no greater potential for predetermined terminal shoot growth after field planting (i.e., number of needle primordia found in the terminal bud). Thus, large-volume container cavities produce a larger seedling that occupies a greater area within the planting spot, without compromising structural balance.

Root growth in spruce seedlings is dependent upon edaphic conditions. Across all three testing environments, there was no relationship between seedlings grown over a range of container volume cavities and root growth (Table 5.1.4.2). Root growth of spruce seedlings usually shows a general trend of greater new root growth with a greater original root system size (Fig. 5.1.2.2b). Root growth of spruce seedlings also varies, depending upon whether the stock type was stored for a spring planting program or fresh-lifted for a summer planting program, the nursery cultural practices, and the genetic source (Section 5.1.2.2). Thus, a larger root system does not necessarily ensure a greater ability to grow roots.

Seedlings of all sizes have similar physiological performance and material stock quality attributes. Interior spruce seedlings grown over a range of container volume cavities had comparable freezing tolerance and drought tolerance or avoidance (Table 5.1.4.2). Photosynthetic capacity was also comparable between seedlings of various sizes over a range of environmental conditions. This indicates that producing a morphologically larger seedling does not confer any additional physiological performance and material stock quality attributes to enhance performance under optimum or limiting environmental conditions. If there is a benefit of a larger seedling in relation to physiological performance, it is that its greater foliar mass allows for greater seedling photosynthetic capacity. This capability could be critical in enhancing the ability to grow quickly and occupy site resources during establishment.

Table 5.1.4.2. Stock type characterization (N = 10–24, depending on test: mean ± SE) of interior spruce seedlings (2+0 stock from the same seedlot) produced in three container volumes for the summer planting program (Grossnickle and Folk, unreported data).

Attribute[a]	415B[b]	415D[b]	615A[b]	Comments
Height	24.2 ± 0.8 cm	29.7 ± 0.7 cm	33.3 ± 0.8 cm	Fits the accepted BCMoF target[c]
Diameter	4.4 ± 0.1 mm	5.0 ± 0.1 mm	6.8 ± 0.2 mm	Fits the accepted BCMoF target[c]
Height to diameter ratio	5.6 ± 0.2	6.0 ± 0.2	5.0 ± 0.2	Fits the accepted BCMoF target[c]
Shoot dry weight	2.83 ± 0.13 g	4.45 ± 0.2 g	6.40 ± 0.3 g	—
Root dry weight	1.06 + 0.06 g	1.40 + 0.08 g	2.06 + 0.10 g	—
Shoot to root ratio	2.84 ± 0.1	3.4 ± 0.1	3.3 ± 0.1	Good balance for drought avoidance[d]
Number of branches	18 ± 1	24 ± 2	33 ± 2	Capability to occupy more area within the planting spot
Number of buds	50 ± 2	67 ± 3	86 ± 3	Capability to occupy more area within the planting spot
Needle primordia in the terminal bud	193 ± 35	164 ± 36	147 ± 38	Good predetermined shoot growth potential
Root growth capacity, optimum	34 ± 3	35 ± 4	30 ± 3.8	Fits the accepted BCMoF target[e]
Root growth capacity, low root temperature (10°C)	24.4 ± 2.5	23.4 ± 3.0	19 ± 2.8	60–70% of optimum RGC
Root growth capacity, after drought (–2.5 MPa)	54 ± 5	38 ± 4	58 ± 7	10–50% greater than optimum RGC
Freezing tolerance at planting (II^f at –6°C)	78 ± 6%	68 ± 5%	77 ± 5%	Comparable to actively growing seedlings (Section 3.7)
Drought tolerance (Ψ_{tlp})	–1.66 ± 0.15 MPa	–1.64 ± 0.09 MPa	–1.49 ± 0.11 MPa	Comparable to actively growing seedlings (Section 2.1.1)
Drought avoidance cuticular transpiration	435 ± 72 mg H_2O (g DW)$^{-1}$ h^{-1}	364 ± 42 mg H_2O (g DW)$^{-1}$ h^{-1}	415 ± 60 mg H_2O (g DW)$^{-1}$ h^{-1}	—

Table 5.1.4.2 (*concluded*).

Attribute[a]	415B[b]	415D[b]	615A[b]	Comments
P_n optimum	2.72 ± 0.24 µmol $m^{-2} s^{-1}$	2.68 ± 0.27 µmol $m^{-2} s^{-1}$	2.09 ± 0.32 µmol $m^{-2} s^{-1}$	Comparable to actively growing seedlings (Section 3.3)
P_n at low root temperature (10°C)	2.12 ± 0.29 µmol $m^{-2} s^{-1}$	1.49 ± 0.12 µmol $m^{-2} s^{-1}$	1.49 ± 0.17 µmol $m^{-2} s^{-1}$	55–80% of optimum
P_n after drought (–2.5 MPa)	2.01 ± 0.32 µmol $m^{-2} s^{-1}$	1.53 ± 0.18 µmol $m^{-2} s^{-1}$	1.36 ± 0.11 µmol $m^{-2} s^{-1}$	55–75% of optimum

[a] Description of attributes are found in Table 5.1.2.4.
[b] All stock types were grown in format 600 Styroblock® containers (Beaver Plastics Ltd.) in the following individual cavity volumes: 415B at 105 mL, 415D at 170 mL, and 615A at 340 mL.
[c] Scagel et al. 1993; BCMoF, British Columbia Ministry of Forests.
[d] Grossnickle and Major 1994*b*.
[e] Section 5.1.2.2.
[f] Index of freezing injury.

PLANTING SPOT LOCATION

Two major factors are considered when choosing planting spots for seedlings. First is the location in which a seedling is planted. After a major disturbance, horizontal and vertical heterogeneity is usually very high, although vertical heterogeneity is primarily present just near the soil surface due to the short stature of vegetation (Spies 1997). Selection of planting spots on these disturbed sites is generally dictated by slash, rocks, debris, depth of organic layer, natural seedlings, and competition across the site. This factor has a very strong influence on growth of the seedling. Second is the target density for the area to be reforested. Every reforestation program has a target for the number of seedlings that are planted for a given area. However, target densities should not be the overriding factor in determining the exact number of seedlings planted in a given area. Planting densities should be based upon the available microsites across the reforestation site.

The local climate broadly reflects regional climate, but microclimatic conditions may vary considerably, depending upon elevation, topography, and aspect. At the microclimate scale, forest canopy removal has a major effect on the radiation balance, which leads to changes in air temperature and relative humidity, thereby affecting VPD. Forest canopy removal also affects the water balance and fertility of the soil. Thus, the selection of a planting spot determines the microclimate surrounding a seedling (Fig. 5.2). The regeneration niche for boreal reforestation sites proposed by Margolis and Brand (1990) provides a generalization of the environmental conditions that seedlings are exposed to on a clear-cut site.

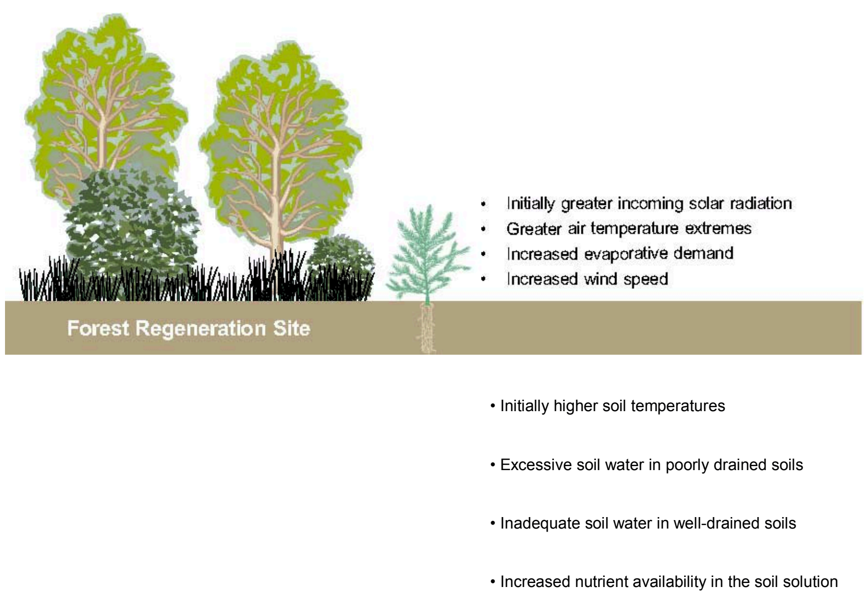


Fig. 5.2. Microsite environmental conditions of the planting spot on a northern latitude reforestation site that can influence the performance of planted spruce seedlings.

These include (*i*) high light intensity, (*ii*) high or low soil water availability, (*iii*) low to medium soil temperatures, (*iv*) high soil surface temperatures, (*v*) high vapour pressure deficits, (*vi*) high incidence of frost, (*vii*) high wind speeds, and (*viii*) high nutrient availability in the soil solution.

Specific details on all of these environmental parameters as they relate to clear-cut reforestation sites have been previously described in Section 1. The environmental changes that occur with the use of a partial forest canopy retention system are discussed later in this treatise (Section 5.6). Foresters must recognize which of these site-specific environmental factors might limit seedling performance on each reforestation site, and they must make the selection of planting spots based on the best available planting microsites.

Environmental factors that determine the planting spot microsite also directly affect the physiological response of spruce seedlings (as described in Section 3). It is important to recognize that reforestation sites have ever-changing environmental conditions and that spruce seedling ecophysiological processes continually respond to these site conditions. Also, seedlings undergo many morphological and physiological changes during the annual cycle, which affects the degree of stress resistance (i.e., both tolerance and avoidance) to environmental conditions (Section 3.9). Field performance is also related to the inherent genetic variation in the physiological performance of spruce seedlings (Section 4). Foresters see the subsequent effect of this dynamic interaction between site environmental conditions and seedling physiological response as field survival and growth performance. Understanding the way in which these physiological processes affect spruce seedling field survival and growth can improve the forester’s capability to make proper planting spot selection and additional silvicultural decisions that impact on plantation performance. It is also critical to realize that the amount of space, both above-and below-ground, between competing vegetation and newly planted seedlings has a direct bearing on microclimate. Early seral stage species with a high level of overall physiological activity and growth are in direct competition with spruce seedlings within this reforestation site environment. Competing vegetation creates microclimates that are ever changing; over time this vegetation alters the environmental conditions of the planting spot (Section 5.5). Understanding the interaction between competing vegetation and the ecophysiological processes of newly planted spruce seedlings is paramount to the selection of desirable planting spots, thereby enhancing the potential for successful development of free-to-grow forest plantations.

PLANTING STRESS

Seedlings can be exposed to stress just after planting on a reforestation site. Stress occurs because reforestation sites can present extreme environmental conditions which alter site heat exchange processes and soil water relations (Miller 1983) (Sections 1.2 and 1.3) (Fig. 5). To ameliorate these conditions, seedlings require a continuous movement of water from absorbing roots to transpiring needles to maintain a proper water balance and ensure survival. The ability of a seedling to take up water is influenced by available soil water, root system size and distribution, root–soil contact, and root hydraulic conductivity (Fig. 5.3a) (Sections 1.3.1 and 2.1.2). Transpirational loss from the needles is determined by the degree of stomatal opening (g_{wv}), needle area, and the atmospheric demand for water (response to VPD, Section 3.2).

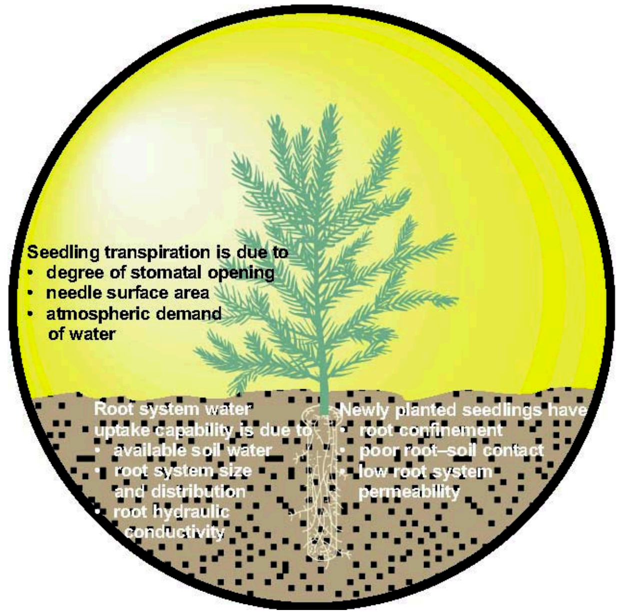


Fig. 5.3*a*. Descriptive representation of planting stress in spruce seedlings.

Typically newly planted seedlings have restricted root placement, poor root–soil contact, and (or) low root system permeability, which can limit water uptake from the soil (Kozlowski and Davies 1975; Burdett 1990). A lack of root development into the soil for newly planted interior spruce seedlings can result in increased seedling water stress (Draper et al. 1985). This occurs because newly planted seedlings, with little root development, have a higher resistance to water movement through the SPAC, which results in lower seedling Ψ at the same level of transpiration as older seedlings with well-developed root systems (Fig. 5.3b) (Bernier 1993). If sufficient root growth does not occur, spruce seedlings continue to be under water stress, and seedling mortality can occur (Hines and Long 1986). New root growth increases the capability of a seedling to access water from a greater soil volume. In addition, new roots can absorb greater amounts of water, thereby reducing the level of root resistance to water movement from the soil through the root and into the xylem (Section 2.1.2). A number of studies have shown that when root growth does occur in newly planted seedlings, an increase in daily seedling Ψ occurs, except under limiting environmental conditions, and seedling physiological processes begin to resume normal functionality (Sands 1984; Grossnickle and Reid 1984b; Carlson and Miller 1990; Brissette and Chambers 1992). The potential for damaging water stress levels is reduced as new root development occurs, thereby improving seedling establishment after planting.

Soil water content can also affect whether planting stress occurs in newly planted seedlings. Near-surface and root-zone soil water deficits can be a major constraint to spruce seedlings on boreal reforestation sites. Root-zone soil water deficits are the result of evaporation from the soil surface and transpiration from competing vegetation (Section 5.5.3). Planting stress can also occur in flooded soil conditions which restrict water uptake by seedlings (Section 3.5.2.2). Planting stress does not occur when newly planted seedlings are exposed to conditions of abundant soil water and (or) low atmospheric evaporative demand. Under these conditions, new root development is not required because the existing root system is adequate to supply water to the shoot system to meet transpirational demand. Thus, various levels of soil water content have a direct influence on whether newly planted seedlings are exposed to water stress.

Planting stress can be affected by the hydraulic properties of the soil system. Soils that are high in organic matter content, within the rooting zone of newly planted seedlings, have an increase in soil porosity, a decrease in bulk density, and an increase in saturated hydraulic conductivity (Section 1.3.1). At soil water contents below saturation, however, soils of high organic matter content can have a decrease in unsaturated hydraulic conductivity (Hillel 1971), which reduces water movement to the roots. For example, Engelmann spruce seedlings planted in soils with high organic matter content had increased seedling water stress throughout the growing season (Grossnickle and Reid 1984b), which resulted in increased mortality (Grossnickle and Reid 1982). In this instance, successful establishment was affected by the hydraulic properties of the soil within the rooting zone.

Planting stress can occur at varying levels of intensity and for varying lengths of time, depending upon how spruce seedlings respond to planting. The following are three examples of planting stress that can occur in newly planted spruce seedlings.

Severe planting stress can be defined by a level of water stress severe enough to limit a major physiological process during most of the daylight period, although not severe enough to cause death (Section 2.1.3). Bare-root white spruce seedlings had very low Ψduring the first 3 weeks after planting (Ψ_{min} < –2.50 MPa) (Fig 5.3c). Initial root growth was detected on these seedlings after 2 weeks, resulting in an increase in daily Ψ_{min} levels (increased to between –2.0 and –2.5 MPa) (Grossnickle and Heikurinen 1989). However, during the first two-thirds of the growing season, Ψ_{min} was lower than or comparable to Ψ_{tlp}. This indicates that during midday, white spruce seedlings were at a level of water stress exceeding the turgor loss point, causing a reduction in physiological processes (Section 2.1.1). These seedlings had not yet developed enough of a root system to access sufficient soil water to meet the transpirational demands placed on the shoot systems. In the final third of the growing season, Ψ_{min} increased as enough root system development occurred, which allowed for sufficient water uptake to meet transpirational demands.

In moderate planting stress, recently planted seedlings are initially exposed to water stress which quickly disappears during the growing season. For example, containerized Engelmann spruce seedlings showed Ψ_{min} ranging between –1.5 and –2.0 MPa over the first month of the growing season (Fig. 5.3c). Initially, these recently planted seedlings had lower Ψ_{min} than seedlings growing for 5 years on the reforestation site. This was due to minimal root development during the first half of the growing season, coupled with high atmospheric evaporative demand and limited water in the upper portions of the soil profile Grossnickle and Reid 1984b). This limited water uptake from the soil resulted in greater resistance to water movement through the SPAC (Fig. 5.3b). By the second half of the growing season, Ψ_{min} was comparable to seedlings growing for 5 years on the reforestation site (Fig. 5.3c). This is because recently planted seedlings had developed sufficient roots to allow for adequate water uptake from the soil.

In low planting stress, recently planted seedlings are never exposed to severe water stress during the growing season. For example, interior spruce seedlings showed no indication of water stress (Ψ_{min} at –1.2 MPa) the first month after planting (Fig. 5.3c). This was due, in part, to access to soil water and low atmospheric evaporative demand throughout the early part of the growing season (Grossnickle and Major 1994b). By early July, the seedlings had enough root development to allow for sufficient water movement through the SPAC, even though soil water declined later in the growing season (Grossnickle and Major 1994b). Seedlings were exposed to water stress only in early July. This was due to seasonal changes in Ψ_{tlp}, rather than a decline in Ψ_{min}. Seasonal increases in Ψ_{tlp} occurred during the period of shoot growth and is a regular growing season phenomenon within the phenological cycle (Sections 2.1.1 and 3.9). During the shoot growth period, spruce seedlings can be exposed to water stress even under conditions of sufficient soil water and even when they have developed root systems capable of water uptake. During the remainder of the season, the seedlings had Ψ_{min} that never declined below –1.4 MPa, indicating that their root systems had sufficient capability to take up water to meet transpirational demands.

The exposure of seedlings to stress is a normal consequence of the process of lifting, storing, handling, shipping, and planting during forest regeneration. Some degree of stress is unavoidable even under the most ideal planting conditions. Planting stress can be mitigated somewhat by planting seedlings with a high stress resistance (Section 5.1.2.4). Also, planting stress can be minimized by preparing favorable planting sites and planting seedlings properly (Rietveld 1989). Lastly, planting stress can be reduced by timing planting to limit exposure to stressful environmental conditions that reduce both physiological response and root growth of the seedlings (Section 3).

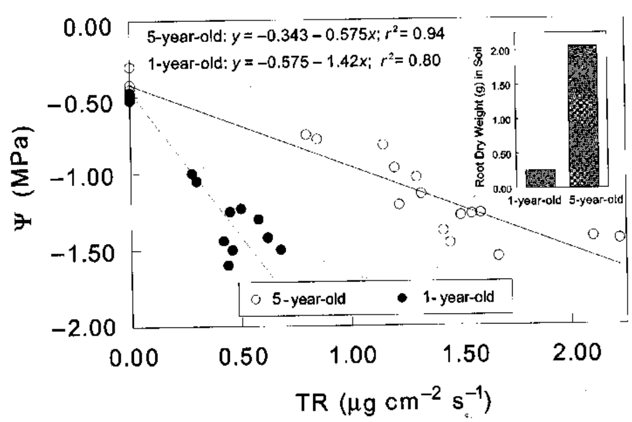


Fig. 5.3b. The relationship between transpiration rate (TR) and shoot water potential (Ψ) for 1- and 5-year-old Engelmann spruce seedlings on an afforestation site. Insert figure represents the amount of seedling root growth out into the soil (adapted from Grossnickle and Reid 1984b).

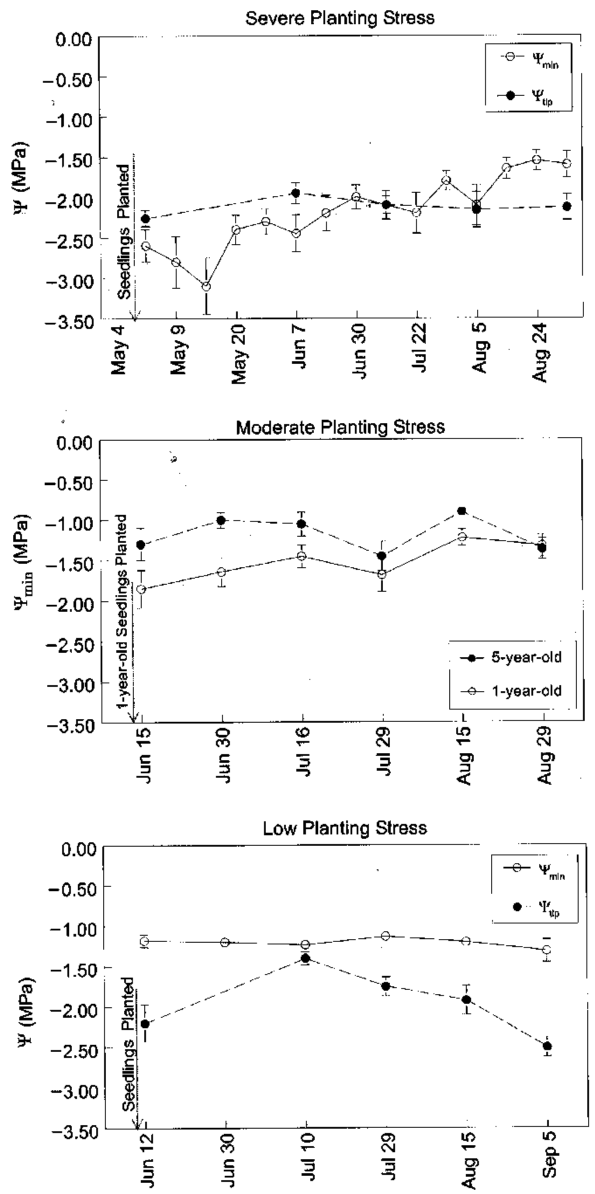


Fig. 5.3c. Examples of varying levels of water stress for newly planted spruce seedlings over a range of reforestation sites. Severe planting stress is represented by bare-root white spruce seedlings planted on a site in northern Ontario (adapted from Grossnickle 1988b and Grossnickle and Heikurinen 1989). Moderate planting stress is represented by container-grown Engelmann spruce seedlings planted on a site in Colorado (Grossnickle 1983). Low planting stress is represented by container-grown interior spruce seedlings planted on a site in central British Columbia (adapted from Grossnickle and Major 1994b). The parameters presented in the figure are minimum daytime shoot water potential (Ψ_{min}), measured between 1200 and 1330 h, and osmotic potential at turgor loss point (Ψ_{tlp}).

ESTABLISHMENT PHASE

Seedlings enter the establishment phase on reforestation sites when they start to develop root systems into the surrounding soil. Therefore, seedlings establish a proper water balance and respond to field site atmospheric conditions without the limitations that can occur when seedlings do not have access to soil water. The establishment phase is a time when seedlings developed as specific stock types or treated with certain nursery cultural practices begin to respond to site conditions. In this section, the performance of container-grown spruce seedlings is examined in relation to short-day nursery cultural effects (as discussed in Section 5.1.1.1), spring and summer planting programs (as discussed in Section 5.1.4.1), and seedling size (as discussed in Section 5.1.4.2). In addition, differences in performance of container-grown and bare-root stock types are discussed. These subsections provide foresters with an appreciation of how various spruce stock types respond to site environmental conditions during the establishment phase.

The establishment phase is also a period when silvicultural practices have reduced the vegetation, thereby creating sites free from competition of established plants (Spies 1997). This occurs because many of the plants found in the understory of the original forest structure have been removed through site preparation or because the original understory has survived the disturbance, but the plants have lost their aboveground parts which may resprout and reoccupy the site at some later date. Before the site is reoccupied with a new vegetation complex, planted spruce seedlings have an opportunity to develop under open site conditions (Fig. 5). As a result, spruce seedlings become exposed to a wider range of environmental conditions (Section 5.2), some of which may be extreme enough to exceed the ability of spruce seedlings to physiologically tolerate environmental stress (defined in Section 3). When this occurs, growth of spruce seedlings on the reforestation site is reduced. On the other hand, this phase can also provide the planted spruce seedlings with ideal environmental conditions that allow for an optimum physiological response and a maximization of their growth potential. An understanding the ecophysiological capability of spruce species in combination with the selection of planting spots that provide desirable microsite environmental conditions can enable foresters to make the proper silvicultural decisions to ensure the planted seedlings respond with rapid plantation establishment.

PERFORMANCE OF SPRING- AND SUMMER-PLANTED SEEDLINGS

Spring-and summer-planted spruce stock types have different growth patterns affecting their morphological development after planting (Section 5.1.4.1). These stock types also have different levels of stress resistance which affect their physiological response to reforestation site environmental conditions (Table 5.1.4.1). Stock type differences can influence seedling performance during establishment and growth phases on reforestation sites.

Spruce seedlings, in general, are planted in the spring from late April through early June or in the summer from late June through early August. Selection of a planting time in either the spring or the summer has a direct bearing on how spruce seedlings initially perform on the reforestation site.

The selection of planting time affects timing of the entire growing season for spring-planted seedlings. After spring planting, spruce seedlings coming out of storage normally require a period of 10–14 days before budbreak occurs (Section 5.1.4.1). The timing of budbreak is dependent upon dormancy status of the seedlings and the thermal input (i.e., warm temperatures) seedlings are exposed to on the field site (Section 2.5). In addition, nursery cultural practices, such as a short-day treatment, can also alter the timing of budbreak (Section 5.4.1.2). After budbreak occurs, spruce species grow for a period of between 8 and 12 weeks, with rapid shoot growth occurring over a 4-week period in the middle of this shoot elongation phase (Section 2.6.1.1). The actual cessation of this shoot growth period is triggered by a reduced photoperiod length and decreasing site temperatures. Thereafter, bud induction and complete development of needle primordia in the bud can take up to another 6 –10 weeks (Section 2.6.1.1). Spring-planted spruce seedlings require from approximately 16 to 22 weeks to complete the process of shoot development. Timing of planting in the spring can determine whether spruce seedlings have a sufficient length of time to undergo all normal shoot development processes before late-summer photoperiods and site temperatures limit this development.

For summer planting, spruce seedlings undergo rapid changes in stress resistance and root growth capability, rather than shoot development, across the planting window. These changes are part of the natural seasonal phenological cycle inherent in spruce species (Section 3.9). Spruce seedlings planted early in the summer planting period typically have a high level of performance (i.e., high Pn capability and high root growth capacity), although a low stress resistance (i.e., drought and freezing tolerance) (Section 5.1.4.1). After budset, these parameters can change quite rapidly over the 4–6-week summer planting window (Sections 5.1.1.1 and 5.1.4.1). These changes can alter the capability of spruce seedlings to properly respond to site environmental conditions.

Table 5.4.1.3. Stock type morphological characterization of interior spruce seedlings (N = 20: mean ± SE) used in spring (FS–1+0) and summer (SP–2+0) planting programs over two growing seasons on a boreal reforestation site (Prince George, B.C., 54° N lat.) (Grossnickle and Folk, unreported data).

	Year 1		Year 2	
Stock type[a]	FS–1+0	SP–2+0	FS–1+0	SP–2+0
New shoot growth (cm)	10.1 ± 1.4	None	5.2 ± 0.2	14.3 ± 1.1
Total shoot height (cm)	29.4 ± 0.8	22.8 ± 0.5	34.3 ± 0.3	34.2 ± 0.6
Diameter (mm)	5.7 ± 0.3	4.2 ± 0.1	8.3 ± 0.3	7.3 ± 0.2
Height to diameter ratio (cm/mm)	4.2 ± 0.3	5.6 ± 0.3	4.1 ± 0.1	4.8 ± 0.2
Number of branches	21 ± 2	10 ± 1	39 ± 4	23 ± 2
Number of buds	98 ± 7	51 ± 3	164 ± 17	126 ± 12
Terminal bud needle primordia	124 ± 18	251 ± 24	—	—
Crown width (cm)	15.4 ± 1.3	11.9 ± 0.4	17.8 ± 0.9	15.6 ± 0.9
Root development into the soil (g DW)	0.6 ± 0.1	0.5 ± 0.1	—	—
Shoot to root ratio (g/g)	1.4 ± 0.2	1.6 ± 0.1	—	—

[a] FS–1+0, frozen-stored 1+0 seedlings planted in early June; SP–2+0, hot-lifted 2+0 seedlings planted in early July.

In the year seedlings are planted on a reforestation site, spring-and summer-planted seedlings have different patterns of morphological development. Spring-planted spruce seedlings have new shoot development, while summer-planted seedlings have no new shoot development (Table

5.4.1.3). Due to this first-year shoot growth, seedlings planted in the spring can have double the number of branches and buds (upwards of 100 buds along their shoots) and a larger crown width than summer-planted seedlings. As a result, spring-planted seedlings have a larger overall shoot system than summer-planted seedlings at the end of the first growing season. This indicates that when both stock types are ready to break bud the following spring, seedlings planted the previous spring have approximately twice the number of locations for shoot growth to occur. Both stock types have comparable height to diameter ratios, root development, and shoot to root ratios after the first growing season, indicating a similar level of overall morphological balance.

Summer-planted seedlings have budset and the initial stages of needle primordia development in the nursery before being shipped to the field. As a result, these seedlings have twice the number of needle primordia in their terminal buds at the end of the growing season when compared to spring-planted seedlings (Table 5.4.1.3). This indicates that summer-planted seedlings have a predetermined shoot growth potential for the next growing season that is twice that of the spring-planted seedlings. If summer-planted seedlings do not have greater predetermined shoot growth potential, this stock type has no strategic advantage over spring-planted seedlings. This was evident in a study on black spruce where the first-year growth advantage of spring-planted seedlings was never made up by summer-planted seedlings even though relative height growth rates were similar over the following growing seasons (Fleming and Wood 1996). It is imperative that nursery cultural practices confer an adequate predetermined shoot growth potential in summer-planted seedlings if this stock type is going to have good establishment on the reforestation site.

During the second growing season, spring-and summer-planted seedlings also have different patterns of morphological development. Summer-planted seedlings have double the rate of new shoot growth as seedlings planted in the spring, which results in both stock types having comparable shoot height and crown width after two field seasons (Table 5.4.1.3). Seedlings planted in the spring still have a slightly larger diameter and thus have a lower height to diameter ratio. Spring-planted seedlings also have a greater number of branches and buds, indicating a greater number of locations for shoot growth to occur in the coming spring. Morphological development over two growing seasons shows the differences between the spring-and summer-planted stock types becoming less noticeable. This indicates that as seedlings grow and become established on the reforestation site, the influence of the original stock type characteristics diminishes.

PERFORMANCE RELATED TO INITIAL SEEDLING SIZE

Spruce seedlings grown in large-volume container cavities have greater shoot and root sizes, which allow the seedling to occupy a greater area within the planting spot (Section 5.1.4.2). These larger seedlings also have a greater number of locations for shoot growth (i.e., greater number of branches and buds), which increases the potential to occupy a greater area within the planting spot. However, a morphologically larger seedling does not have additional physiological performance and material stock quality attributes that enhance performance under optimum or limiting environmental conditions (Section 5.1.4.2). A benefit of a larger seedling in relation to its physiological performance is the potential for greater seedling photosynthetic capacity. This ensures faster growth, thus the potential for rapid site occupation and access of site resources during the establishment phase. It is this greater size of the root and shoot systems that confers any additional benefit to larger seedlings during establishment on the reforestation site. However, foresters must recognize that large planting stock can provide both benefits as well as risks to the establishment of a forest plantation.

Planting larger seedlings can be beneficial to seedling establishment. A number of studies have found that planting larger, compared to smaller, conifer seedlings on sites with vegetation competition resulted in better growth up to 8 years after planting (Balneaves 1989; Newton et al. 1993; South et al. 1993; South et al. 1995; Zwolinski et al. 1996). This pattern was also evident in field trials with Sitka (South and Mason 1993), white (McMinn 1982b), and black spruces (Jobidon et al. 1998). In the study on black spruce (Jobidon et al. 1998), larger stock had a greater exposure to the growing season PAR available to shoot systems over a 3-year period, which resulted in greater shoot growth (Fig. 5.4.1.4). Spruce species have a rapid increase in Pn as PAR increases to approximately 25% full sunlight, with a continued gradual increase in Pn at further increases in light, and this has a direct effect on shoot growth (Section 3.1). Competition for light between planted seedlings and competing vegetation is one of the main limiting environmental factors that affect the performance of seedlings in the transitional phase of plantation development (Section 5.5.1). The use of larger seedlings may be a good silvicultural strategy if vegetation competition is a major factor limiting plantation establishment.

Larger container-grown stock size does not confer an advantage over the surrounding competition unless the size difference is large enough to dramatically improve field performance. Paterson (1997) planted black spruce container-grown stock with a modest range in size (i.e., 23.1–19.6 cm in height and 2.7– 2.0 mm in diameter) and found that, after 5 years, survival and current annual height increment were comparable, although originally larger stock was still bigger. These findings indicate that larger container-grown stock needs to be originally large enough to capture more of the site resources from the competition in order to justify its use in a reforestation program.

Planting seedlings of larger size can also create risks in establishing a plantation. This may occur where limiting environmental conditions can put seedlings with a large shoot to root balance under physiological stress. Under dry soil conditions, larger conifer seedlings had greater water stress (Rose et al. 1993; Stewart and Bernier 1995) or reduced growth (Baer et al. 1977; Hahn and Smith 1983) than smaller seedlings. Under dry conditions, black spruce seedlings with very large shoot systems (i.e., six times the foliar mass of small seedlings) had greater water stress and reduced Pn compared to seedlings with smaller shoot systems (Lamhamedi et al. 1997). As the seedling shoot system reaches a certain size, the increased foliar mass can increase the seedling's susceptibility to water stress. This can be a problem in newly planted seedlings that have restricted root development. The susceptibility of larger seedlings to be exposed to water stress at planting is mitigated if seedlings have the capability to quickly develop new roots. Large container-grown Engelmann spruce seedlings had increased first-year survival compared to smaller seedlings (Hines and Long 1986). Hines and Long (1986) found that increased survival in larger seedlings was related to greater root growth over the initial 4-week period after planting, which reduced seedling water stress (i.e., Section 5.3: Planting stress). In most instances, spruce seedlings show a general trend of greater new root growth with a greater original root system size (Section 5.1.2.2), which allows larger spruce seedlings to generate enough roots to reduce the shoot to root balance and avoid planting stress conditions. However, increased root growth does not always occur in larger seedlings having bigger root systems (e.g., Fig. 5.1.2.2b and Table 5.1.4.2), and this variability can be related to stock type, nursery cultural practices, and genetic source. In addition, restricted root development of newly planted seedlings can be limited by field site edaphic conditions (Section 3.5). Caution should be used when considering whether to plant large stock on sites that can limit initial seedling establishment.

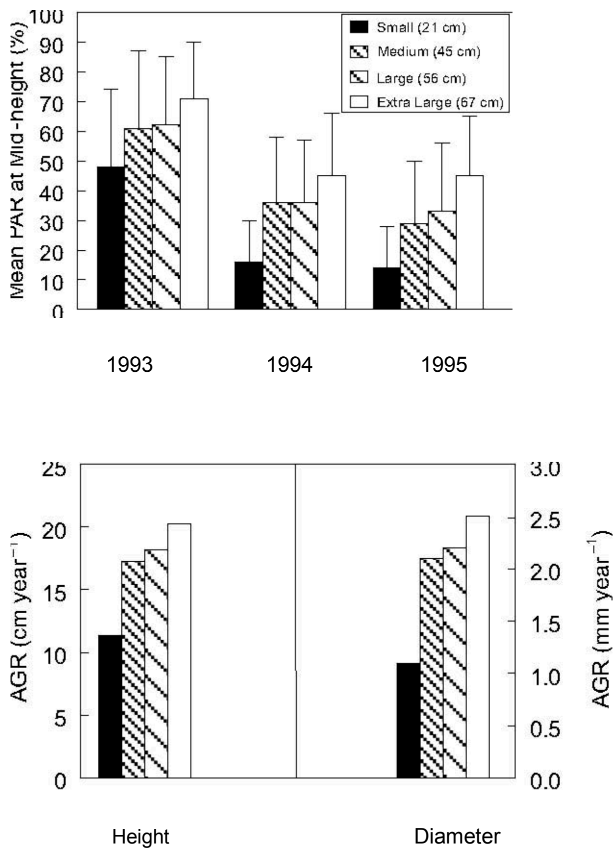


Fig. 5.4.1.4. The mean percentage of photosynthetically active radiation (PAR) transmitted at the mid-height of black spruce seedlings of four initial sizes, and mean absolute growth rate (AGR) for height and diameter over the 3-year period on a reforestation site in southern Quebec (adapted from Jobidon et al. 1998).

FROST HEAVING

Frost heaving occurs on regeneration sites that have fine-textured soils with a high amount of soil water and exposure to below-freezing air temperatures (Section 1.2.5). When site air temperatures are just below freezing, temperatures in the upper soil layer fluctuate around 0°C, resulting in the formation of ice lenses. These ice lenses cause seedlings to frost heave. Newly planted seedlings are susceptible to the process of frost heaving due to lack of adequate root system development needed to anchor the seedlings into the soil (Örlander et al. 1990; Goulet 1995).

The primary effects of frost heaving on the physiological performance of newly planted seedlings fit into two categories (Goulet 1995). First, frost heaving lifts the seedling root system out into the air and exposes roots to desiccation. Second, frost heaving causes the breakage of newly developed roots and reduces effective root–soil contact. Frost heaving creates conditions that disrupt water flow through the SPAC pathway by reduction of root system size and distribution, and disruption of root–soil contact, thereby causing planting stress (i.e., water stress) to be prolonged (Section 5.3). Long-term effects of frost heaving include reduced seedling establishment and growth on reforestation sites.

Field performance of frost-heaved spruce seedlings is restricted because of planting stress. Spruce seedlings planted in exposed mineral soils on sites prone to summer frost have reduced survival, with frost heaving a primary cause of increased mortality (Nobel and Alexander 1977; Shaw et al. 1987). In a number of instances, reduction in shoot development of spruce seedlings was directly attributed to frost heaving (MacGillivray and Hartley 1973; Söderstöm 1973; Low 1975; Zalasky 1980). The loss of growth in some white spruce plantations was attributed to an annual natural pruning of roots through frost heaving, leaving root systems either deformed or partially exposed (Sutton 1992). Root deformity in young spruce seedlings due to frost heaving has long-term implications on plantation performance because it reduces stability, thus increasing potential blow-down within the plantation (Shaw et al. 1987; Sutton 1992).

Frost heaving can be exacerbated or mitigated by silvicultural regeneration practices. On some sites, removal of overstory vegetation can create conditions conducive to frost heaving (Graber 1971). Sutton (1970) found that white spruce seedlings that appeared to be well established, when released from weeds, were heaved from the soil through frost action. Also, site preparation treatments that removed the organic surface layer from fine-textured soils increased the incidence of frost heaving (Fig. 5.4.2). Frost heaving can be controlled by retention of some overstory cover, mulching of exposed mineral planting spots, or through site preparation techniques that create microsites having an overlying organic layer (e.g., inverted humus mounds). In addition, deep planting of large stock is recommended under certain conditions (i.e., where high water tables and (or) low soil temperatures do not occur) to ensure adequate root development, keeping seedlings firmly anchored into the soil (Örlander et al. 1990; Goulet 1995).

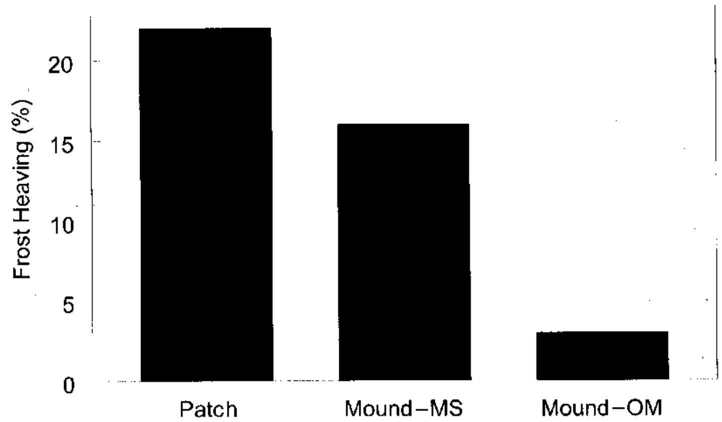


Fig. 5.4.2. Frost heaving frequency of container-grown conifer seedlings planted on a sandy-silt moraine under various site preparation treatments in northern Sweden (adapted from Örlander et al. 1990). Mounds were located on mineral soil (MS) or organic matter (OM).

SUMMER FROST AND LATE-WINTER DESICCATION

Summer frosts occur due to radiative heat loss from the ground surface under clear night sky weather conditions or to the movement of cold air downslope through the advection process (Section 1.2.3). These frosts primarily occur at the beginning and end of the growing season, although frost can occur at any time of the year on clearcut reforestation sites within the boreal forest. On sites where cover vegetation has been removed, air temperatures near the soil surface (at 5–10 cm) can be 2–6°C lower than air temperatures found under a vegetation canopy (Stathers 1989; Örlander et al. 1990; Groot and Carlson 1996; Groot et al. 1997), causing a greater number of frosts to occur during the growing season on a reforestation, compared to forested, site.

Freezing temperatures during the summer months coincide with the period in which spruce seedlings are at their lowest level of freezing tolerance (Section 3.7.4). Any exposure to freezing temperatures causes a reduction in physiological performance and morphological development (Section 3.3.1). Most of the frost damage in field-planted spruce seedlings seems to be confined to the buds, newly flushed needles, and succulent shoots of spruce seedlings (Clements et al. 1972; Stiell 1976; Örlander et al. 1990; LePage and Coates 1994), and these are the shoot structures that have the lowest level of freezing tolerance during the growing season (Section 3.7.4).

The time at which spruce seedlings are exposed to frost during the growing season affects subsequent morphological development (Grossnickle, personal observation). Bud development is arrested when frost damages the bud during the initial stages of bud activity, prior to budbreak, in the spring. Damaged buds look viable, yet do not break bud. When a severe enough frost occurs as shoots are emerging, shoot systems can be damaged. Damaged shoots turn brown and fall off the seedling, leaving no visible damage to the shoot system. When a lethal frost occurs after the shoot system has elongated, the needles turn brown and fall off, leaving the dead stem. After any of these frosts, no new shoot growth occurs from the damaged shoot in that growing season.

During the growing season that follows a damaging frost, shoot growth of spruce seedlings occurs from lateral buds just below the damaged region of the shoot system (Grossnickle, personal observation). If the terminal shoot is damaged, a number of the lateral shoots can grow upwards, resulting in a forked top. Usually, although not always, one of these new terminal shoots becomes dominant after a number of years. Lateral branches can develop a “bushy” structural appearance due to the loss of a terminal bud or shoot to a frost. This creates a seedling with a compact shoot structure that has many lateral branches within the crown. Frosts that damage shoots have a marked effect on subsequent growth patterns of seedlings. This damage is manifested although a reduction in shoot growth as well as an alteration of the shoot form. This reduction in subsequent shoot development due to a severe summer frost can reduce the capability of spruce seedlings to become established on reforestation sites.

Frosts during the growing season are considered the chief problem in establishing tree plantations in northern latitude forests (Sakai and Larcher 1987). In addition, the number of frosts tends to increase with decreasing levels of competing vegetation. There is a greater occurrence of frosts causing damage to young plantations of spruce seedlings on open sites compared to forested sites (Clements et al. 1972; Harding 1986; Christersson and von Fricks 1988; Sutton 1992; Groot and Carlson 1996; Tanner et al. 1996). The percentage of white spruce seedlings with moderate or severe damage as a result of spring frosts increases dramatically at >20% exposure to the sky (Fig. 5.4.3a). Geiger (1980) reported that there is a direct relationship between the size of a forest clearing (i.e., up to 3 ha in size) and the lowest night temperatures, which increases the chances of a frost occurring during the springtime. On a frost-prone site, 71% of interior spruce seedlings had frost damage at the end of the first growing season where vegetation cover was <15% (LePage and Coates 1994). Further development of interior spruce height growth over a 5-year period was reduced due to frost damage, where vegetation cover ranged from 8 to 17%. Alternative silvicultural systems that retain a partial forest canopy reduce the frequency of frosts; this is discussed later in this treatise (Section 5.6).

On sites subjected to frequent summer frosts, reductions in cover may be more detrimental than beneficial to the initial performance of spruce seedlings. White spruce seedlings under a vegetation canopy had higher seasonal Pn in the spring and fall than open-grown seedlings, and this was attributed to reduced exposure to freezing temperatures for seedlings covered by vegetation (Man and Lieffers 1997). Ball (1994) suggests that the optimum regeneration niche on open field sites are microsites that protect seedlings from both radiative frosts and intense sunlight, as this combination of environmental conditions is known to cause damage to the photosynthetic system in spruce seedlings (Section 3.3.1).

In the long-term, interior spruce height growth was greatest on sites where vegetation was <8%, indicating that seedlings can ultimately outgrow the potential for frost damage, given reduced competition for site resources (LePage and Coates 1994). Thus, spruce seedlings can reach a shoot size that is not influenced by the site microclimate near the soil surface where frosts are prone to occur.

On sites with no vegetation cover, site preparation treatments can sometimes reduce the number of frosts that occur during the growing season. Treatments such as burning, scalping, trenching, and mounding can decrease the risk of radiation frost damage to conifer seedlings (Stathers 1989; Steen et al. 1990; Örlander et al. 1990) (Fig. 5.4.3b). These treatments allow for the mixing of warm overlying air and for airflow to occur near the soil surface, thereby increasing air temperature by just a few degrees (Stathers 1989). Removal of grass and surface organic layers can also decrease the risk of radiation frosts. In cold, wet areas, mineral mounds that raise the seedling out of the cold air layer can be effective in reducing the risk of radiation frosts (Steen et al. 1990). Planting seedlings near large stumps or fallen logs may also provide additional heat through the reradiation of stored energy during the night (Spittlehouse and Stathers 1990). This microsite effect can cause enough of an increase to bring temperatures above the critical freezing mark and prevent damage to actively growing seedlings during the growing season.

There have been reports of extensive damage to spruce seedling plantations during the first postplanting winter (Herring and Letchford 1987; Krasowski et al. 1993a, 1995). This damage has been attributed to freeze desiccation. When the snowpack melts during the late winter and early spring, shoots can be exposed to above-freezing daytime air temperatures, plus increased light and VPD during the late winter and early spring (Krasowski et al. 1995). Shoot systems exposed above the snowpack undergo water stress that can become lethal if the frozen soils limit water uptake required to meet the low transpiration levels of partially open stomata and (or) cuticular transpiration occurring as shoots are exposed to late-winter and springtime evaporative demand of the air (Section 3.7.5). It is unclear whether this is a persistent problem for seedlings on sites that have the potential for low snowpack or whether 3–4 years of deep snowpack are required to allow seedlings to grow to a size that reduces the risk of overwinter shoot damage due to winter desiccation.

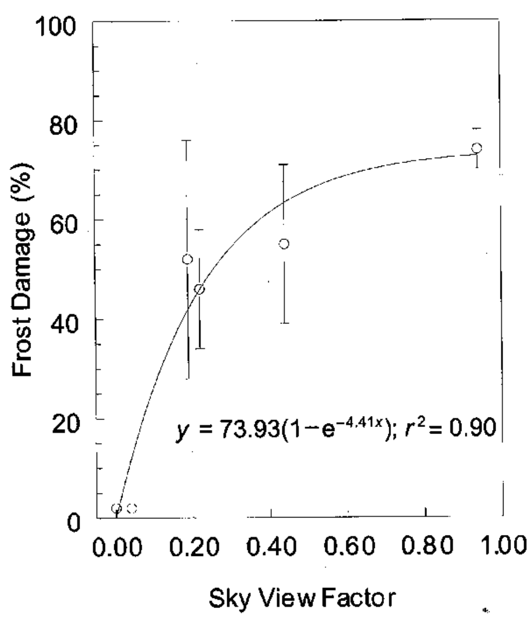


Fig. 5.4.3*a*. Incidence of medium to heavy summer frost damage to white spruce seedlings versus the sky view factor of the opening (adapted from Groot and Carlson 1996).

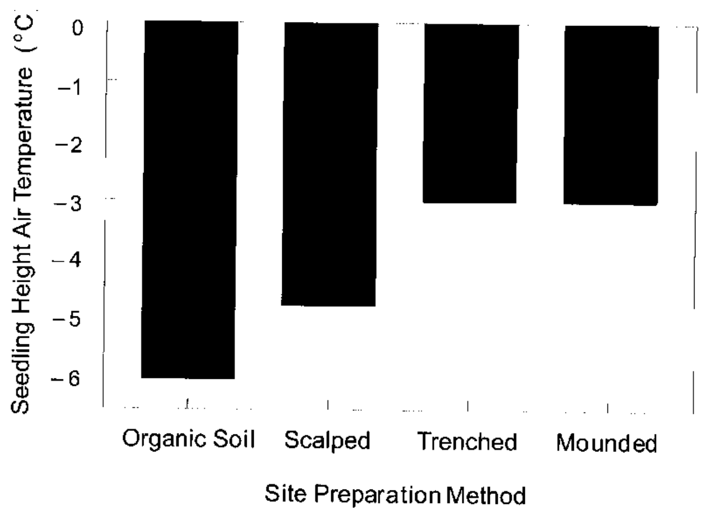


Fig. 5.4.3*b*. The lowest air temperature at seedling height in different site preparation treatments during a nighttime summer frost on a northern latitude reforestation site (adapted from Stathers 1989).

Freeze desiccation is believed to be exacerbated by the root development patterns of recently planted container-grown spruce seedlings (Krasowski et al. 1996). Spruce seedlings grown in containers initially have roots that develop primarily out of the bottom rather than the top portion of the container plug (Section 2.6.2.2). During the late winter and early spring, the soil in the boreal forest is typically frozen to a depth beyond 5 cm, with soil temperatures consistently below 5°C until early May (Stathers and Spittlehouse 1990; Krasowski et al. 1995) (Section 1.2.1). Since the majority of water-absorbing roots of recently planted container-grown seedlings are in the frozen portion of the soil profile (i.e., from 5 to 15 cm in depth), Krasowski et al. (1996) theorized that seedlings cannot absorb enough water to meet the transpirational demand placed upon their shoot systems. The ability of spruce seedlings to take up water from the soil decreases dramatically as soil temperatures decline to freezing, with water uptake through the roots being nonexistent in frozen soil (Section 3.5.1), which can result in increased seedling water stress (Section 3.7.5). Krasowski et al. (1996) noted that naturally established and older container-grown seedlings did not visibly suffer from desiccation injury and had more extensive root systems throughout the soil profile; this may have helped these seedlings to avoid late-winter and early-spring desiccation. A lower incidence of desiccation injury occurred in seedlings planted on plowed sites or on planting mounds (Krasowski 1996), and these microsites may have afforded deeper daytime thawing of the soil profile during the late winter and early spring, enabling spruce seedlings to take up sufficient soil water to prevent desiccation injury.

HIGH SOIL SURFACE TEMPERATURES

High soil surface temperatures can occur on open reforestation sites within the northern latitude forest as the result of site and atmospheric factors. First, soil surfaces with high organic matter content and dark coloration have a higher capacity for heat build-up (Section 1.2.4). In certain instances, soil surface temperatures can exceed 50°C on open reforestation sites throughout the northern latitude forest region. Second, clear sunny days and a lack of wind to dissipate heat build-up along the soil surface create atmospheric conditions causing an increase in air temperature (Section 1.4), which leads to high VPD (Section 1.3.2) at seedling shoot height. An increase in soil surface temperatures typically increases the VPD of the air just above the soil surface (Ripley and Redmann 1976). This is why sites that can have high soil surface temperatures provide a poor microenvironment for seed germination and seedling establishment (Smith 1951; Vaartaja 1954; Hungerford and Babbitt 1987).

Conifer seedling shoots can be damaged when soil surface temperatures exceed 50°C on reforestation sites (Maguire 1955; Helgerson 1990). Seedlings express heat damage through formation of lesions or abnormal swelling of the stem near the soil surface (Helgerson 1990). In a study of western conifers, Engelmann spruce was determined to have the lowest level of tolerance to high temperatures (Seidel 1986). Actively growing spruce seedlings have shoot damage at temperatures that exceed 45°C, with the level of damage increasing due to either the length of exposure or to exposure to higher temperature conditions (Section 3.3.2). White (MacHattie and Horton 1963) and Engelmann (Nobel and Alexander 1977) spruce mortality on reforestation sites has been attributed to high temperatures.

In many instances, high but nonlethal soil surface temperatures during the summer alter the diurnal physiological processes of planted spruce seedlings. For example, on clear sunny days with no wind along the soil surface, surface temperatures of dark-colored soils reached up to ~40°C, resulting in increased midday VPD (Fig. 5.4.4). Engelmann spruce seedlings grown in this dark organic matter were exposed to 18% higher needle temperatures (~3–5°C) and 33% greater VPD during the early afternoon, when compared to seedlings growing in grey mineral soil. These atmospheric conditions caused a reduction in g_{wv} for Engelmann spruce seedlings growing in the dark organic matter compared to mineral soil. This reduction in g_{wv} occurred even though all seedlings had similar Ψ_{pd} (i.e., –0.45 and –0.40 MPa for seedlings growing in the dark organic matter and mineral soil, respectively). A reduction of g_{wv} under higher VPD is a typical response for spruce seedlings (Section 3.2).

The application of silvicultural practices to alter the structure or constituency of the soil surface, or reduce the amount of incoming solar radiation received at the soil surface, mitigates the potential of heat damage to recently planted spruce seedlings (Helgerson 1990). Practices such as removing surface litter or organic matter from the base of seedlings reduce heat load to the seedling stem. Planting seedlings on the north-facing side of trenches or furrows created through mechanical site preparation treatments also reduce heat loads. Shade from natural site features such as rocks, stumps, and coarse woody debris can also reduce soil surface temperatures. Shading through artificial means (e.g., shade cards) or by leaving an adequate overstory vegetation cover can also reduce the risk of seedling exposure to high soil surface temperatures. These same silvicultural practices can create microsites having low soil temperatures, which are also known to limit spruce seedling performance on northern latitude reforestation sites (Section 3.5.1). Before applying these types of silvicultural practices to recently planted spruce seedlings, foresters need to identify whether a high soil surface temperature is likely to be a site environmental factor limiting spruce seedling performance.

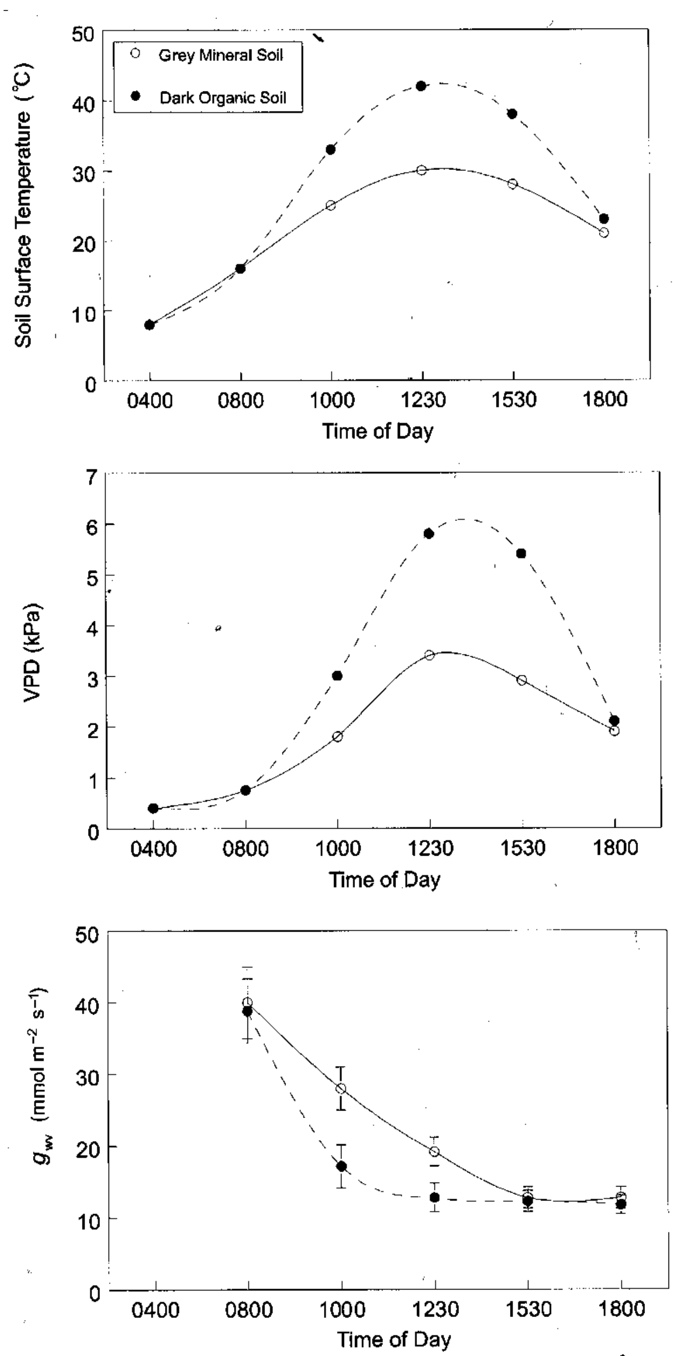


Fig. 5.4.4. Diurnal pattern of soil surface temperature, vapor pressure deficit (VPD) measured at seedling height, and needle conductance (g_{wv}) for Engelmann spruce seedlings on a clear sunny summer day for microsites having either a grey mineral soil or dark organic matter soil surface layer (adapted from Grossnickle and Reid 1984b).

FLOODING

Flooded soils can occur on northern latitude reforestation sites located in low-lying peatlands or bogs, poorly drained alluvial valley bottoms, and floodplains of river valleys. Flooding causes forest soils to become anaerobic (Section 1.3.1) and have low thermal diffusivity (Section 1.2.4), which keeps soils cold throughout the growing season. These soil conditions lead to reduced physiological activity (i.e., gas exchange and nutrient uptake) and growth of spruce seedlings (Sections 3.5.2.2 and 3.6.1). If flooded conditions are severe, planted seedlings undergo stress and possibly die (Section 3.5.2.2). Silvicultural practices that raise the elevation of the planting spots, modify the aboveground microclimate, or increase the drainage of water from the site have led to improved seedling establishment on sites prone to flooding.

Site preparation treatments that raise the planting spots above the water table have been effective in improving spruce seedling establishment. Raised planting spots provide sites of increased soil aeration for seedlings planted in soils where there is a high water table (Macadam 1988; McMinn and Hedin 1990; Sutton 1993; Yole and Kranabetter 1996a) (Fig. 5.4.5a). The raised planting spots also increase soil temperatures throughout the growing season (Macadam 1988). These raised planting spots provide a location for boreal conifer seedlings to develop roots into the soil (Söderstöm 1981; von der Gönna 1989) so they can become established and have enhanced shoot growth (Söderstöm 1981; Schaible and Dickson 1990; Hånell 1992). For example, black spruce seedlings planted on raised planting spots had greater shoot growth over two growing seasons (Fig. 5.4.5b). This improved growth was attributed to better aerated soils and warmer rooting zone temperatures in the raised planting spots, which allowed for improved nutrient uptake, resulting in an increase in both needle N and Ca concentrations (Roy et al. 1999). The long-term growth (i.e., over 8 years) of interior spruce seedlings can be improved by up to 40% by using raised planting spots on sites with seasonally wet soils (Macadam and Bedford 1998). Raised planting spots also provide a microtopographic position that increases the survival of seedlings in flooded soils (Macadam and Bedford 1998; Roy et al. 1999), although if the water table drops during the growing season, these raised spots can cause seedling water stress and higher mortality (Rothwell et al. 1993).

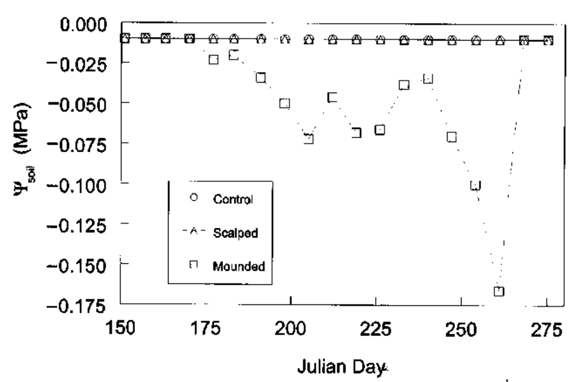


Fig. 5.4.5a. Soil water potential (Ψ_{soil}) at 10 cm throughout the growing season for different site preparation treatments in hygric soils on a boreal reforestation site in north-central British Columbia (adapted from Macadam 1988).

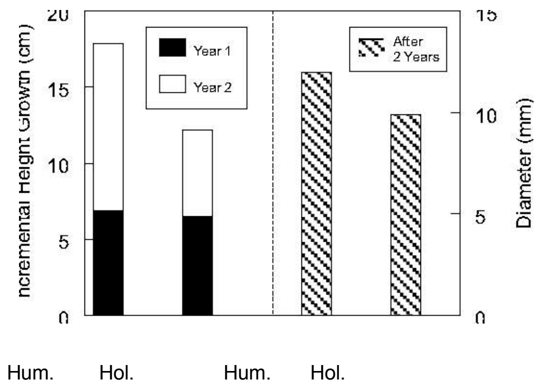


Fig. 5.4.5b. Height growth and diameter of black spruce seedlings on hummock and hollow planting spots over two growing seasons in a wetlands boreal reforestation site (Forêt de Beaurivage, Que., 46° N lat.) (adapted from Roy et al. 1999). Average depths of the aerobic layers were 26.2 and 15.1 cm on hummocks and hollows, respectively, over the two growing seasons.

Site preparation treatments that remove vegetation and slash from the soil surface (i.e., windrowing or broadcast burning) can increase the radiation reaching the soil surface, thereby increasing evaporation from the soil surface and causing a moderate reduction of soil water in saturated soils (Yole and Kranabetter 1996a). Aerated soils also have a higher thermal diffusivity that allows greater heat penetration downward into a moist, compared to saturated, soil profile (Section 1.2.4). Opening up low-lying reforestation sites can also increase air temperatures at the soil surface and improve the soil temperatures within the effective rooting zone of recently planted seedlings.

Site preparation treatments that remove water from poorly drained reforestation sites also improve the growth of planted spruce seedlings. In this silvicultural practice, ditches are cut (i.e., 0.5–1.0 m in depth) across the contours of a site to increase drainage, thereby lowering the water table and increasing soil temperatures (Lieffers and Rothwell 1987) and nutrient availability (Lieffers and MacDonald 1990; MacDonald and Lieffers 1990) in the upper portions of the soil profile. Drainage of reforestation sites can improve height (Lieffers and Rothwell 1986; Wells and Warren 1997), diameter (Seppälä 1969), and root growth (Adams et al. 1972; Lieffers and Rothwell 1986) of recently planted spruce seedlings. The frequency of ditching across poorly drained sites can also influence seedling performance, with the shoot growth of black spruce seedlings declining as the spacing of the ditches across the site increases from 3 to 15 m (Wells and Warren 1997). Also, distance of the planting spots from the drainage ditch can affect seedling performance; black seedlings had improved shoot growth when planted 5 m from the ditch, while seedling performance was not improved when planted at further distances from the ditch (Roy et al. 1999). The frequency of ditching and the location of planting spots from the drainage ditch must be properly determined to ensure that adequate drainage from the upper portion of the soil profile provides microsites that can improve seedling growth.

The improved aeration that occurs within the soil profile in the years after ditching can create conditions favorable for microbial activity, which can cause a subsequent release of nutrients (Sivola et al. 1985). This phenomenon has resulted in an increase in foliar N, P, and K concentrations of black spruce needles over a number of years after site drainage (Mugasha et al. 1993). The level of N mineralization after ditching is dependent upon the inherent fertility of the organic substrate (Wells and Williams 1996). Sites with low fertility may require nutrient amendments with fertilizers (e.g., P: Dickson 1971), further soil aeration through tilling (Wells and Williams 1996), or the combination of both practices (Wells and Warren 1997) to provide an adequate mineralization of N for growth of peatland spruce plantations. Fertilization of black spruce with N, P, and K on drained sites resulted in increased needle concentrations of these nutrients, and elevated N concentrations resulted in a concomitant increase in needle mass (Mugasha et al. 1993, 1999). This indicates that seedlings planted on drained low fertility sites would respond to fertilization. If ditching is going to be used as a site preparation practice, fertility of the organic substrate needs to be determined to ensure that the silvicultural prescription for low fertility sites also includes fertilizer amendments.

Soil water conditions created through ditching can change considerably after as little as 2–3 years due to peatland subsidence (Rothwell et al. 1996; Prévost et al. 1997). This collapse of surface peat soils through physical settling and (or) increased organic matter decomposition has the potential to change the hydrologic, thermal, and aeration properties of the soils that spruce seedlings are planted into on low-lying reforestation sites. Roy and associates (1999) found that, 2 years after ditching, this phenomenon caused a comparable depth of the aerobic layer in the soil surface horizons between planting spots located from 5 to 60 m from the drainage ditch. Soil surface subsidence may create a situation where ditching only provides a short-term improvement in aeration in the upper portions of the soil profile of northern latitude reforestation sites prone to flooding.

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