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Stock Quality Assessment: Forecasting Survival or Performance on a Reforestation Site

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Seedlings are exposed to a wide range of environmental conditions on reforestation sites. These conditions could result in stress that reduces survival and/or growth of newly planted seedlings. Field survival and field performance potential need to be distinct areas of evaluation when selecting and interpreting stock quality tests. Tests that measure the functional integrity of seedlings help forecast their survival capability. Tests that simulate anticipated field environmental conditions help forecast a seedling's physiological performance and potential for growth on a reforestation site. Tree Planters' Notes 44(3): 113-121; 1993.

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 1989, Hawkins and Binder 1990, Johnson and Cline 1991, Omi 1991). The wide array of testing procedures has sometimes led to confusion in selection of tests for specific purposes. Part of this confusion stems from the fact that stock quality tests can have one of two different purposes: evaluating nursery development (for example, determining nursery growth phase or evaluating readiness for lifting and storage) or forecasting field survival and/or growth (Duryea 1985b). A clearer understanding of the nature and purpose of specific testing techniques will help nursery personnel and regeneration silviculturists choose appropriate tests and make more effective decisions.

With any type of stock quality assessment procedure, differences in test results could be due to species, genetic variability of seedlots, variations in nursery culture, cold or frozen storage regimes, and variations in testing conditions. Separate testing standards need to be developed for seedlings produced from various combinations of the above nursery decisions. Seedling users also need to be aware that the mishandling of stock during transport to planting sites, improper planting procedures, and unpredictability of field site environmental conditions will influence how test results agree with initial seedling survival and/or growth on a reforestation site.

Stock quality assessment as it relates to forecasting either initial field survival or field performance potential (i.e., potential for initial growth on a reforestation site) is the focus of this paper. Testing procedures are discussed and evaluated for their suitability to provide information on these aspects of stock quality assessment. Understanding the benefits and limitations of these testing approaches will provide nursery personnel and regeneration silviculturists with a better appreciation of their potential utility within an operational forest regeneration program.

Planting Stress and Stock Quality Assessment

Seedlings can be exposed to stress just after they are planted on a reforestation site. This is usually attributable to water stress because root confinement, poor contact of roots with soil, and low root system permeability can limit water uptake from the soil needed to meet transpirational demands placed upon seedling shoot systems by atmospheric conditions (Kozlowski and Davies 1975, Burdett 1990). Planting stress will be overcome only if seedlings have functional physiological processes required for morphological development, primarily root growth, to occur. When root growth occurs in newly planted seedlings, water stress is reduced and a seedling's physiological processes then have the capability to respond in a normal manner (Sands 1984, Grossnickle 1988, Carlson and Miller 1990, Brissette and Chambers 1992).

Further limitations on the physiological processes of newly planted seedlings can occur from exposure to environmental extremes on a reforestation site. The most dramatic of these are alterations in heat exchange processes and site-water relations (Miller 1983). Low temperature and drought conditions are two predominant types of environmental stress occurring on reforestation sites.

First, freezing events can cause frost damage (Nilsson and Eriksson 1986, Grossnickle et al. 1991b) and/or reduced gas exchange capability (Neilson and Jarvis 1976, DeLucia 1987, Grossnickle and Arnott 1992) in newly planted seedlings. Low soil temperature conditions in early spring can cause reduced root growth (Nambiar et al. 1979, Lopushinsky and Kaufmann 1984, Grossnickle et al. 1991b), and/or restrict water uptake, resulting in water stress (Kaufmann 1977, Nambiar et al. 1979, Lopushinsky and Kaufmann 1984, Grossnickle 1988).

Second, newly planted seedlings can be exposed to drought through limited soil moisture and/or high evaporative demand conditions of the atmosphere. Drought conditions cause seedling water stress by restricting water uptake from the soil (Kaufmann 1979, Dixon et al. 1983, Grossnickle and Reid 1984, Sands 1984, Livingston and Black 1987a, Brissette and Chambers 1992) and by inadequate stomatal control as evaporative demand increases (Grossnickle and Blake 1987, Livingston and Black 1987b, Grossnickle and Arnott 1992). The result of increased water stress in newly planted seedlings is a reduction in growth (Nambiar and Zed 1980, Margolis and Waring 1986, Livingston and Black 1988, Grossnickle and Heikurinen 1989). As a result, planting stress can be exacerbated by field site environmental conditions that reduce growth and delay a seedling's capability to occupy the site.

No stock quality assessment program can alleviate the stress seedlings are exposed to on reforestation sites. However, a program that defines a seedling's functional integrity could determine whether it has the capability to survive potentially stressful environmental conditions, because initial field survival is dependent on whether a seedling has the physiological capability to function normally at time of planting. On the other hand, a program that defines field performance potential by measuring a seedling's physiological responses and morphological development under simulated environmental conditions of the Planting site would provide information on field growth potential. Though testing for field performance potential would provide information on survival capability, there is no guarantee that testing for survival would provide sufficient information on field performance potential. Thus, stock quality assessment as it relates to a seedling's initial field survival or field performance potential are considered distinct areas of evaluation and are examined as separate topics.

Field Survival Capability

Currently, there are a number of testing procedures that provide information on the initial survival potential of operationally produced stock. These tests measure a seedling's vitality under a specific set of conditions that defines a certain level of quality when tested (Ritchie and Tanaka 1990, Langerud 1991). These kinds of tests measure the functional integrity of seedlings, which helps determine their initial survival capability. Functional integrity indicates whether a seedling is, or is not, damaged to the point of limiting primary physiological processes. The intent of these testing approaches is 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).

The following are examples of testing procedures that provide information on the functional integrity of tested seedlings. 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 culture regime or from a similar seed source, by measuring a subsample from the entire population. A brief description of each test is given below. Further specific information on each testing procedure can be found in the cited articles.

1. **Root growth capacity** is a measure of a seedling's ability to regenerate new roots and an indirect measure of a seedling's overall physiological condition (Stone 1955, Ritchie and Dunlap 1980, Rit chie 1985, Burdett 1987, Ritchie and Tanaka 1990, Sutton 1990).
2. **Oregon State University vigor test** is a measure of a seedling's subsequent survival after exposure to a single controlled stress event (15 minutes at 30 °C and 30% relative humidity) (McCreary and Duryea 1985, 1987; Lavender 1988).
3. **Shoot water potential** of potted seedlings after a set time period is an indirect measure of a root system's capability to absorb water and thus maintain a proper seedling water balance (McCreary and Duryea 1987).
4. **Needle conductance** (Orlander and Rosvall-Ahne brink 1987) and **transpiration** (Langerud et al. 1991) are measures of the water movement capability of needles and an indirect measure of a root system's capability to absorb water and the xylem's capacity to transport water to the needles.
5. **Infrared thermography** is a measure of foliage heat exchange (i.e., temperature) resulting from transpiration and an indirect measure of a root system's capability to absorb water and the xylem's capability to transport water to the needles (Weatherspoon and Laacke 1985, Orlander et al. 1989).

6. **Root system water loss capability** measured under positive pressure is an indirect measure of root system integrity (Ritchie 1990).
7 **Fine root electrolyte leakage** is an indirect measure of root system integrity (McKay and Mason 1991, McKay 1992).
8. **Variable chlorophyll fluorescence** is a measure of photosynthesis and an indirect measure of a seedling's overall physiological condition (Vidivar et al. 1989, 1991).
9. **Stress-induced volatile emissions** is a measure of cell injury due to membrane breakdown (Hawkins and DeYoe 1992).

The above tests measure different morphological or physiological parameters in relation to initial field survival of tested seedlings. Seedlings that do not meet certain minimum performance standards usually have poor field survival capability. On the other hand, seedlings that meet certain minimum performance standards have a greater capability to survive under typical reforestation site conditions.

However, no single testing procedure accurately forecasts field survival under all circumstances. For example, an extensive operational test of root growth capacity (RGC) found that RGC had a poor relationship with field survival under some circumstances (Binder et al. 1988). Seedlings with poor RGC had a higher probability of increased mortality. However, they found that even seedlings with high RGC could still have an unacceptable mortality level after field planting. This example emphasizes the limitations inherent in using a single test as an indicator of a seedling's overall quality. Seedlings have a wide array of physiological processes that continually respond to environmental conditions. Proper stock quality assessment must consider the dynamic and interdependent nature of a seedling's physiological processes.

Field Performance Potential

A seedling's performance on a reforestation site depends on its inherent growth potential and the degree to which the environmental conditions of the field site allow this growth potential to be expressed. Thus, the degree to which a seedling can adapt to site conditions just after planting influences its initial growth on the reforestation site (Burdett 1983). To determine a seedling's field performance potential, the seedling should be assessed in relation to anticipated environmental conditions at the site (Duryea 1985b; Sutton 1982, 1988; Puttonen 1989; Grossnickle et al. 1988, 1991a; Hawkins and Binder 1990). In addition, an array of morphological and physiological tests that examine factors important for determining a seed ling's field performance potential is required because stock quality reflects the expression of a multitude of physiological and morphological attributes (Ritchie 1984). An array of tests that simulate anticipated field environmental conditions would help forecast seed lings physiological performance and potential for growth on a reforestation site.

To measure a seedling's physiological response and growth under a range of environmental conditions, tests should define performance under optimum environmental conditions, as well as define stress tolerance and avoidance parameters (Levitt 1980). This approach was first presented by Timmis (1980), who developed a series of tests to simulate essential physiological responses and growth behavior of seedlings in any environment and derived numerical values for these responses. Examples of possible material and performance attribute tests important in defining a seedling's field performance potential are shown in table 1. In tests measuring performance attributes, whole seedlings are subjected to some test condition that integrates their response over time or to a range of environmental conditions (Ritchie 1984). In tests measuring material attributes, an individual morphological or physiological parameter of the seedling is tested (Ritchie 1984).

Seedlings are normally exposed to some type of stress after planting on a reforestation site. Anticipated environmental conditions could be defined by reforestation silviculturists during on-site development of regeneration prescriptions. Test environments could then be selected that match this range and combination of anticipated environmental conditions.

Effective determination of field performance potential depends on the selection of a smaller number of morphological and physiological attributes from a master table (table 1). As described earlier, low temperature and drought are two predominant types of environmental stress that could occur on reforestation sites. Possible attributes to consider measuring on seedlings to be planted on potentially cold or droughty reforestation sites are described in figures 1 and 2, respectively. This approach to stock quality assessment is designed to allow the user to have information from a number of material and performance attribute tests that are important for their intended purpose.

Results from testing programs could be integrated to develop a means of expressing the overall physiological and morphological quality of seedlings. The performance potential index (PPI) has been developed to integrate material and performance attribute tests for a comprehensive perspective of seedling field per-

Table 1 -*Possible material (morphological and physiological) and performance attribute tests and their intended purposes for defining field performance potential*

Morphological attribute tests

Height: General measure of photosynthetic capacity and transpirational area (Armson and Sadreka 1979); greater height is an advantage on sites where brush competition and animal browsing are potential problems (Cleary et al. 1978).

Diameter: General measure of a seedling's durability, root system size, and protection from drought and heat damage; provides support to withstand physical abuse (Cleary et al. 1978).

Needle surface area: Direct measure of potential photosynthetic or transpirational surface area.

Root surface area or dry weight: Good indicator of absorptive root surface (Thompson 1985).

Needle primordia: Important indicator of shoot growth potential (Colombo 1986).

Seedling water balance ratio (needle dry weight/[stem diameter x root dry weight]): Measure of drought avoidance potential for situations where water absorption lags behind transpiration (Grossnickle et al. 1991 a).

Physical attribute tests

Osmotic potential at turgor loss point: Quantitative measure of drought tolerance (Tyree and Jarvis 1982).

Maximum bulk modulus of elasticity: Quantitative measure of cells' elasticity, with greater elasticity representing greater turgor maintenace (Tyree and Jarvis 1982).

Seedling water movement: Measurement of water movement capability in relation to a plant's resistances along the pathway (i.e., root xylem, needle) to the atmosphere (Hinckley et al. 1978); provides measure of drought avoidance potential.

Cuticular transpiration: Measure of needle's capability to avoid water loss after stomata have theoretically closed (Vanhinsberg and Colombo 1990).

Days to terminal budbreak: Direct measure of bud dormancy status (Lavender 1991) and indirect measure of changes in drought and cold temperature tolerance (Burr 1990).

Performance attribute tests

Root growth capacity: General indicator that all systems in a seedling are functioning properly (Ritchie 1984) and measure of seedling performance potential (Burdett 1987).

Root growth capacity at low root temperature or after exposure to drought conditions: Measure of a seedling's performance and root growth capability under stressful soil conditions (Grossnickle et al. 1991 a).

Frost hardiness: Measure of a seedling's tolerance to freezing temperatures (Glerum 1985).

Net photosynthesis 14-day integral under optimal environmental conditions: Direct measure of a seedling's photosynthetic capability (Grossnickle et al. 1991 a).

Net photosynthesis 14-day integral at low root temperatures: Direct measure of seedling tolerance to low temperatures (Grossnickle et al. 1991 a).

Net photosynthetic capability at decreasing predawn water potentials: Direct measure of a seedling's tolerance to drought (Grossnickle et al. 1991 a).

Gas exchange capability at various vapor pressure deficits: Measure of stomatal conductance, transpiration, and/or net photosynthesis used to define the efficiency of a plant's CO_2 uptake in relation to water loss (Landsberg 1986).

formance potential (Grossnickle et al. 1991c). The PPI provides a means for collectively interpreting the results from a group of tests within a standardized, yet quantitative framework. The PPI, measured immediately before planting, has been used to clarify the relationship between nursery culture regimes (Grossnickle et al. 1991a-c) or stock types (Grossnickle and Major 1993a,b) with field performance. Another approach to integrating test results has been proposed by D'Aoust et al. (1991). Their approach characterizes seedling performance potential with ten morphological and physiological parameters. Principal component analysis was used to identify a smaller set of parameters that adequately represent information contained in the whole set. Measurement of four variables (i.e., diameter, stem height, shoot water potential at planting, and root growth capacity) before field planting were sufficient to characterize the morphology and physiology of the seedlings produced.

However, limitations are inherent in stock quality assessment depending on when the test is used and what morphological and physiological attributes of the seedlings are measured (Puttonen 1989). These limitations influence the usage of test results. Because these tests are conducted just prior to planting, their ability to forecast seedling growth on a reforestation site has a limited time frame. Consequently, a number of studies have reported various levels of success in forecasting growth on a reforestation site (Grossnickle et al. 1991a-c; Grossnickle and Major 1993 a,b; Major et al. 1993; Folk et al. 1993).

Inconsistencies in forecasting seedling growth in the field are due to several factors. First, errors in describing potential seedling performance can occur in a system that aggregates many plant physiological and morphological characteristics (e.g., cells, tissues, and organs) having different turnover times (Gardner et al. 1982). Seedlings have a dynamic pattern to their seasonal physiological response and morphological devel-

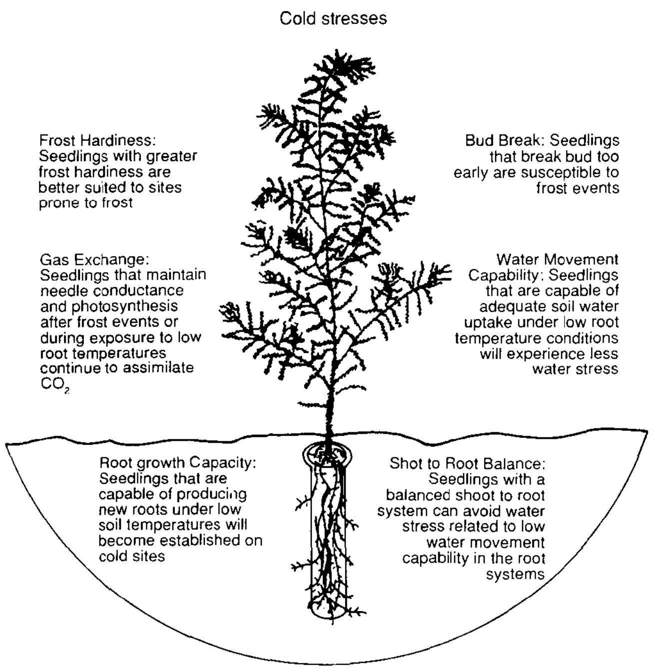

Figure 1 *-Possible testing procedures for determining seedling field performance potential in response to cold reforestation site environmental conditions.*

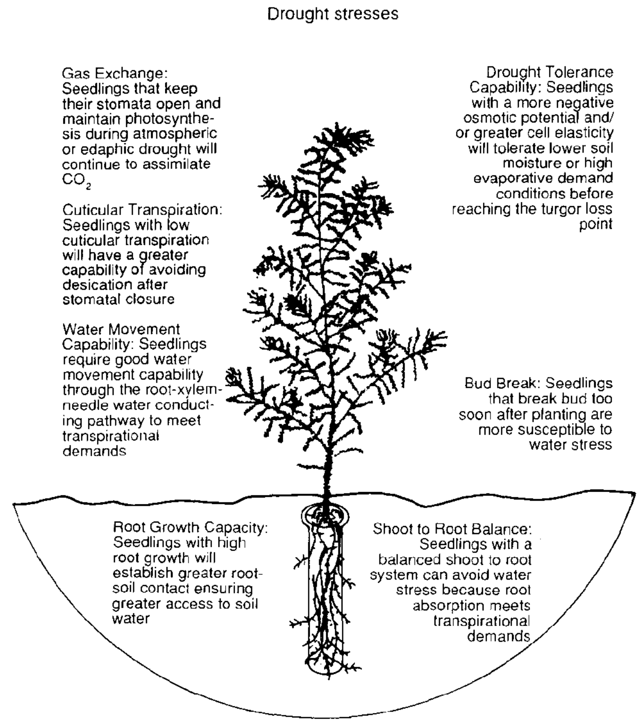

Figure 2 *-Possible testing procedures for determining seedling field performance potential in response to drought reforestation site environmental conditions.*

opment (Fuchigami et al. 1982, Burr 1990, Ritchie and Tanaka 1990). 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. Second, seedling field site performance may not always match stock quality test results because it is difficult to simulate all possible combinations of environmental stress-that is, duration, timing, intensity, frequency-that could occur under actual field site conditions. This makes it difficult to always define the proper level of environmental stress needed to obtain useful information on field performance potential that would forecast growth of seedlings on reforestation sites.

This does not mean that forecasting seedling field performance potential is not possible. One could come closer to defining a seedling's actual field response by using a greater number of material and performance attribute tests designed to give information on a seedling's overall response to potentially limiting site related environmental conditions. Also, information on typical seasonal trends of environmental conditions, for reforestation sites within defined ecosystems, could be used to develop test environments that provide a fair representation of what seedlings might be exposed to in the field. With this information, attributes such as those in table 1 could be selected to characterize a seedling's response to expected environmental conditions of a specific planting site.

In the following example, we describe how actual field response was forecasted by using a combination of material and performance attribute tests. Field performance potential was measured, under controlled laboratory conditions, on western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) seedlings destined for late winter planting when exposure to low temperature conditions was probable (Grossnickle et al. 1991a). Western hemlock seedlings treated with short-day (compared to long-day) dormancy induction treatments had better field performance potential in the following tests (table 1, figure 1):

1. Water movement capability through the plant atmosphere continuum at 5 °C root temperature.
2. Net photosynthesis 14-day integral with root temperature at 5 °C.
3. Root growth capacity at a root temperature of 5 °C.

4. Frost hardiness of the whole shoot system to -18 /C.
5. Seedling water balance ratio.

One month after planting on a reforestation site, and after exposure to low temperatures and frosts in late winter and early spring, short-day treated seedlings had the least needle damage due to frosts and the greatest amount of new root growth (Grossnickle et al. 1991b). In addition, short-day treated seedlings had greater needle conductance and net photosynthesis after frost events during this late winter and early spring period (Grossnickle and Arnott 1992). In this example, material and performance attribute tests were selected in anticipation of low-temperature site conditions just after planting. This group of tests yielded a fairly accurate forecast of subsequent field performance.

Attributes defined in table 1 are not an all-inclusive list, but an example of parameters to consider for a comprehensive stock quality assessment program. Inclusion of alternative material or performance attribute tests in the master table is possible depending upon the user's needs and further development of testing procedures. A number of authors have identified additional seedling physiological and morphological characteristics that might be important for inclusion in a master table (Timmis 1980, table 1; Burdett 1983, table 1; Puttonen 1989, table 2). Material and performance attribute tests need to be developed with these physiological and morphological characteristics in mind.

Conclusions

Stock quality testing procedures that measure the functional integrity of seedlings at time of planting help to forecast initial survival capability. A number of testing approaches are available that determine whether stock meets certain minimum physiological standards, thus allowing for removal of seedlings with poor field survival capability.

On the other hand, testing for field performance potential requires a separate approach to forecast seedlings physiological response and growth on a reforestation site. A combination of material and performance attributes tests, designed to provide information on a seedling's physiological response and growth to potentially limiting site-related environmental conditions, comes closer to defining actual field performance. Whether this approach is practical in all operational reforestation programs is questionable.

The sophisticated equipment and technical expertise required to conduct field performance potential testing, as has been described, will limit its use. One can speculate that field performance potential testing could be beneficial to nursery personnel in developing new stock types or nursery cultural regimes. Regeneration silviculturists could use field performance potential testing when planting seedlings on field sites where survival and/or growth is known to be limited. Field performance potential testing has been used in our lab to test seedlings from a number of operational reforestation programs where field site conditions or stock type performance was considered limiting to reforestation success.

Stock quality testing using the above described approaches would provide a means for nursery personnel and regeneration silviculturists to better forecast initial field survival capability or field performance potential of seedlings. With this information, forest regeneration programs can work towards producing seedlings that meet the definition of stock quality-"fitness for purpose."

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