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# Quantifying root system quality of nursery seedlings and relationship to outplanting performance

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**Abstract.** With over 1.5 billion forest tree seedlings produced annually in the USA, seedling quality assessment is critical to ensure reforestation success. While height and root-collar diameter are the most common traits evaluated during seedling quality assessment, above-ground morphology is not always an accurate predictor of performance after outplanting. Root system morphology and physiological status may provide a more accurate indication of seedling potential. However, relatively few studies have attempted to quantitatively assess root system quality in relation to outplanting success. Large root volume, high root fibrosity, and an increased number of first-order lateral roots have shown some correlation to improved field performance. Physiological seedling quality assessment is commonly practiced through evaluation of root growth potential. Other tests, such as root electrolyte leakage, have also shown some potential as measures of seedling physiological quality. This review identifies current methods of assessing seedling root system quality and discusses potential shortcomings of these methods. An increased understanding of the suitability of current tests, coupled with the development of new tests and multiple parameter relationships, may foster the development of species and site-specific targets for seedling root system quality assessment. The production of seedlings with root systems that meet high morphological and physiological standards better enables seedlings to rapidly establish and thrive upon outplanting.

## Introduction

Approximately 5% of the world's forests are plantations, comprising a total area of 187 million ha (FAO 2001). In the USA, over 1.5 billion forest tree seedlings are produced annually, and more than 1 million ha of plantations are established each year (USDA-FS 1999). It is expected that an increased proportion of the world's wood supply will come from tree plantations (Pandey and Ball 1998; Hartley 2002). Therefore, plantation establishment is necessary to maintain forest cover and the provision of forest products. Successful plantation establishment depends on the use of seedlings whose morphological and physiological characteristics meet targets associated with favorable growth and survival under an anticipated range of site conditions.

Quality seedlings are those which will meet a desired level of growth and survival upon outplanting (Duryea 1985; Mattsson 1997), and do so at an affordable cost. Seedling quality is directly related to genetic composition, size, vigor, and expected environmental conditions upon outplanting, and is influenced by handling, planting, and storage practices. A number of papers and reviews have discussed seedling quality (Sutton 1979; Ritchie 1984; Duryea 1985; Puttonen 1989; Grossnickle and Folk 1993; Mattsson 1997; Mohammed 1997; Puttonen 1997; Sampson et al. 1997; Tanaka et al. 1997). However, these reviews have focused largely on above-ground morphology and whole plant physiological vigor, and less so on root system quality. Thus, there has been little synthesis of research related specifically to morphological and physiological attributes of root systems. Therefore, the objectives of this review are to (1) identify current methods of assessing seedling root system quality, and (2) discuss potential shortcomings of these methods with the intention of providing direction towards future research in this area.

## Above versus below-ground parameters

Seedling morphology is easily measured (Ritchie 1984) and is the most common form of seedling quality assessment. Height and root-collar diameter are widely used to assess the quality of nursery seedlings, and in many cases these variables have been correlated with seedling survival and/or growth after outplanting (Thompson 1985; Bayley and Kietzka 1997; Jacobs et al. 2005). However, it has long been realized that height and diameter alone do not correlate with field performance in all cases (Chavasse 1977; Thompson and Schultz 1995; Jacobs et al. 2005). Wakeley (1949) found that, for southern pines, there was often only a weak relationship between seedling height in the nursery and survival after outplanting. Stone (1955) determined that seedling physiological condition (expressed by root growth potential) at outplanting could indicate potential for root and shoot growth, as this variable largely determined the capacity of the seedling to mitigate drought stress. In the half-century since these studies, relatively little research has focused intensively on the assessment of root system quality. In many ways, this is because root system measurement and analyses are difficult, time consuming, and often inaccurate due to their below-ground nature (Bouma et al. 2000; Costa et al. 2001).

Successful seedling establishment is largely dependent on the capacity of seedlings to rapidly initiate new roots (Grossnickle 2005). The production of new roots can mitigate the effects of transplant shock or planting check, terms used to describe the reduced growth of seedlings caused by acclimatization to new environmental conditions immediately following outplanting (Rietveld 1989). One of the main causes of transplant shock is water stress (Burdett 1990; Haase and Rose 1993), which results from poor root proliferation and insufficient root–soil contact (Burdett 1990). This problem may be pronounced in the case of bareroot seedlings, where root–soil contact is highly disrupted through the loss of fine roots at lifting (Nambiar 1980; Struve and Joly 1992). New root growth helps to alleviate this problem (Burdett et al. 1984; Nambiar and Sands 1993). In conifer seedlings, new root growth is largely dependent on current photosynthesis (van den Driessche 1987; Burdett 1990) and high seedling water potential immediately after outplanting is favorable for initiating new root growth (Burdett 1990).

Selection of appropriate seedling stocktypes can help minimize transplant shock when effectively matched with environmental conditions on the outplanting site. Root system morphology can differ extensively depending on stocktype. Given that container seedlings maintain their entire root system, including fine roots, when outplanted, transplant shock can be considerably reduced through their use (Miller 1999; BCMOF 2001). Container seedlings also tend to maintain higher water potential during the first year following outplanting compared to bareroot seedlings (Dixon et al. 1983; Crunkilton et al. 1992; Davis 2003). Reduction of transplant shock can lead to increased survival and growth rates; Vyse (1981) estimated that in spruce plantations transplant shock could equate to the loss of 1 or 2 years of growth.

The ability to effectively anticipate potential for seedling root proliferation following transplanting could greatly improve our ability to enhance field establishment. Since measurement of above-ground morphological parameters have not consistently served as strong predictors of field performance, it is logical to incorporate below-ground morphological and physiological parameters in an attempt to better predict seedling performance following outplanting.

## Assessing root system properties: morphological parameters

Morphological measurements of root systems can be time consuming and destructive, which may be a major reason that there has been relatively little research conducted on the predictive nature of these parameters. Root system morphology can be influenced by fertilization (Brissette 1991; Jacobs et al. 2004), irrigation (Williams et al. 1988; Brissette 1991; Bayley and Kietzka 1997), and root pruning (Larson 1975). Container seedling root system morphology can be affected by the growing media and associated physical properties, container treatments (Arnold and Struve 1993), the size and shape of containers (Funk 1971; Aphalo and Rikala 2003), and the spacing of the containers (Aphalo and Rikala 2003). In addition to soil physical properties, bareroot seedling root system morphology is altered through growing density as well as undercutting and wrenching (van den Driessche 1983; Kainer and Duryea 1990; Schultz and Thompson 1990, 1997). Seedling responses to nursery cultural practices vary by species and nursery locale. A variety of assessment techniques have been developed to accurately characterize root system morphological quality and in many cases these measures have been quantitatively linked to outplanting performance.

*Root system fibrosity*

A fibrous root system has a high water and nutrient absorption area and a large number of active root tips, which benefit seedling establishment (Thompson 1985; Deans et al. 1990a). However, root system fibrosity is a poorly defined term at present, and therefore it has been difficult to develop a standardized assessment of this characteristic. Tanaka et al. (1976) described fibrosity as the percentage of root dry weight represented by lateral roots. Using another approach, Kainer and Duryea (1990) counted total lateral root length for all lateral roots ≥2 cm in length, sampled 10% of these roots, and then counted the number of root tips. Deans et al. (1990a) described fibrosity in terms of the number of higher-order lateral roots per seedling. While these studies all found that greater root system fibrosity resulted in better field performance, the lack of a standardized approach makes fibrosity a difficult test to apply. Furthermore, the tedious and time consuming nature within the range of present-day fibrosity assessment techniques provides little potential for transfer to operation. Thus, development of a more rapid and standardized assessment of fibrosity would allow for better and more frequent application of this method. Such a system, based on inputs including species, anticipated site conditions, and above-ground morphology could help provide an accurate characterization of root system quality.

*Root volume*

Measurement of seedling root volume became popular starting in the mid-1980s as a means of evaluating seedling root system size. Seedling root volume can be assessed non-destructively using the water displacement method (Burdett 1979). A drawback associated with this method is that it does not differentiate between fine and coarse roots, and therefore has limited capacity to characterize root system architecture (Thompson 1985). Several studies (Rose et al. 1991a, 1991b, 1992, 1997; Jacobs et al. 2005) found positive relationships between seedling root volume and field survival and/or performance. Two years after outplanting, ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) seedlings with larger initial root volumes ( $>7$ $cm^3$) had significantly higher survival than those with smaller root volumes ( $<4.5$ $cm^3$) (Rose et al. 1991b). In that study, seedlings in the larger root-volume category also had greater height growth after 2 years than those in the smaller root-volume category (10.3 vs. 6.4 cm). In a similar study with Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco.) seedlings, height growth after one growing season was significantly greater in a larger root-volume category ( $>13$ $cm^3$) than in a smaller category (<9 $cm^3$); however, differences were no longer significant after the second growing season (Rose et al. 1991a).

Haase and Rose (1993) found that Douglas-fir seedlings with larger root volumes were better able to mitigate the effects of transplant shock except in the case of extensive moisture stress. When loblolly pine (*Pinus taeda* L.) seedlings were not exposed to drought conditions, seedlings with large root volumes had greater hydraulic conductivity than those with smaller root volumes (Carlson 1986). With high moisture stress, however, seedlings with larger root systems may not necessarily have greater capacity to alleviate water stress following transplanting. For instance, Jacobs et al. (2004) found that Douglas-fir seedlings with larger root volumes at the time of transplanting had similar water potential values during summer as those with lower root volumes. Seedlings with larger root volumes could initially be at a disadvantage following transplant because of corresponding greater leaf area, which acts to increase water loss due to higher transpirational demand. For example, in a greenhouse study investigating recovery of bareroot northern red oak (*Quercus rubra* L.) seedling after simulated drought stress, seedlings with larger root volumes were less able to mitigate drought stress than those with smaller root volumes (Jacobs et al. in press). This suggests the importance of coordinating seedling root system specifications with the intended outplanting site characteristics.

*First-order lateral roots*

The concept of using first-order lateral roots (FOLR; number of roots ≥1 mm in diameter at junction with tap root) as a measurement of seedling quality was proposed by Ruehle and Kormanik (1986) for northern red oak. This and other studies (e.g., Kormanik 1986; Thompson and Schultz 1995; Dey and Parker 1997; Ponder 2000; Ward et al. 2000; Noland et al. 2001) have found positive relationships between the number of FOLR and performance of forest tree seedlings. A drawback to using the number of FOLR is that this method does not accurately characterize the entire root system. For example, the actual diameter and length of individual FOLR as well as the number and size of higher-order lateral roots are not accounted for with this method (Jacobs et al. 2005). In a study comparing the effectiveness of various parameters as predictors for growth of northern red oak, white oak (*Q. alba* L.), and black cherry (*Prunus serotina* Ehrh.), root volume was a better predictor than FOLR for both oak species, but not for black cherry (Jacobs et al. 2005). Additionally, Ponder (2000) found no relationship between FOLR and height growth after 4 years for black walnut (*Juglans nigra* L.) and white oak, and no relationship between the number of FOLR and survival of northern red oak, white oak, black oak (*Q. velutina* Lam.), or black walnut.

As with root volume, there has been limited application of FOLR across a variety of species and site conditions, and it is therefore difficult to assess its general potential as a means of quantifying root system quality. However, given positive relationships between FOLR and field performance this method may be useful in assessing seedling root system quality.

*Root system area and length*

Root system length and area provide a quantitative description of seedling root systems and can also be measured non-destructively. Similar to previously described measures, a number of studies have shown positive correlation between these variables and field performance. In a study of Austrian pine (*Pinus nigra* Arnold), the number of root tips was considered a less efficient predictor of seedling vigor than total root length (Chiatante et al. 2002). Greater lateral-root length was associated with higher leaf gas exchange rates in Shumard oak (*Q. shumardii* Buckl.) seedlings (Gazal and Kubiske 2004). Root system area, measurement of which is comparable in accuracy to root volume but more time consuming (Racey 1985), can be measured photometrically (Morrison and Armson 1968), by dipping in adhering gel and recording the change in gel volume (Wulster 1985), or by cross-sectional area (Sundström and Keane 1999). While measurement of root system length has been considered too time consuming for operational use (Thompson 1985), technological advancement in the development in the accuracy of root system scanners could greatly improve the viability of root length as a morphological indicator of root system quality; the same technology could be applied to measurement of root area (Rigney and Kranzler 1997).

*Assessing morphology of seedling root systems*

As evidenced by the number of tests available for assessing seedling root system morphology, quality can be effectively tested by a variety of means. The lack of direct comparisons among these variables both within species and under similar outplanting conditions, however, makes it difficult to directly compare the efficacy of these methods. Consistent results from the use of root volume as a predictor of outplanting success over a relatively wide range of species suggests its general applicability in root system quality assessment. Root area may be worthy of more detailed examination in coordination with technological advancements in photometric tools. An important consideration that must be accounted for in any morphological test of root system quality is the silvics of the species being grown, and the importance of realizing how a test interacts with those silvics. Therefore, the need exists to continue to test these methods across more species and a broader range of outplanting conditions to better define applicable and accurate ranges of these parameters; thus, caution must be used in interpreting any of these results beyond the scope of the studies conducted. Furthermore, integration of multiple parameters to account for a broader characterization of root system architecture may result in an increase over the ability of any single method to predict field performance.

## Assessing root system properties: physiological status

Incorporation of measurements of seedling physiological status into quality assessment is a logical step. Physiological testing can be used to predict the impact of various stresses on seedling performance upon outplanting (McKay 1997). As seedling root systems are often more susceptible than shoots to stresses such as cold damage and desiccation (Deans et al. 1990b; Bigras and D'Aoust 1993; Bigras and Margolis 1997), rapid tests of physiological status of root systems are needed (Hawkins and Binder 1990).

As is the case with seedling morphology, the physiological status of seedling root systems can also be altered through nursery cultural practices such as fertilization and irrigation (Bayley and Kietzka 1997). Photoperiod, growing temperature, and container size and shape can all influence the physiological status of container-grown tree seedling roots (Bigras and D'Aoust 1993). Bareroot seedling root physiological status, in terms of water potential and root growth capacity, are influenced by seed bed density, undercutting, and wrenching (van den Driessche 1983; Brissette 1991). Seasonal timing of these practices can also yield different physiological responses. The following section describes some of the methods that have been used in assessing seedling root physiology.

### *Root growth potential*

Root growth potential (RGP) has become a standard component of seedling quality assessment in many operational nurseries (Dunsworth 1997) and is the most common physiological measurement performed on seedlings in North America (Simpson and Ritchie 1997). Thorough reviews by Ritchie and Dunlap (1980) and Simpson and Ritchie (1997) cover this topic in detail, and thus we present only a short description of the significance of this test. While RGP is not a measure of actual physiological status, it is a representation of the expression of multiple physiological parameters, including dormancy status, carbohydrate content, nutrient status, and moisture content, under a given set of environmental conditions. Defined as '*the quantified ability of a tree seedling to initiate and elongate new roots within a prescribed period of time in a standard environment optimized to promote root growth*' (Simpson and Ritchie 1997), this test is performed by counting the number and length of new roots or by measuring the change in root volume of a representative sample of a seedling crop over a fixed amount of time. Numerous papers have extolled the virtues of RGP as an accurate predictor of survival or growth for species such as ponderosa pine (Stone and Jenkinson 1971), Sitka spruce (*Picea sitchensis* [Bong.] Carr.) (Deans et al. 1990a), lodgepole pine (*Pinus contorta* Dougl. ex Loud.)

(Burdett et al. 1983; Simpson 1990), Douglas-fir (Simpson 1990), western hemlock (*Tsuga heterophylla* [Raf.] Sarg.) (Simpson 1990), interior spruce (*Picea glauca* [Moench] Voss × *Picea engelmanii* Parry) (Simpson 1990; Simpson et al. 1994), and ash (*Fraxinus excelsior* L.) (O'Reilly et al. 2002).

Despite its widely accepted use in seedling quality assessment, RGP is not considered to be an ideal test for predicting outplanting success. Many of the questions regarding the acceptability of RGP as a measurement are based on the difference between the optimal conditions of the test and the actual outplanting conditions (Binder et al. 1988; Simpson and Ritchie 1997). Burdett (1987) posited that RGP may be an indicator of seedling cold hardiness and stress resistance, as RGP was inversely related to cold damage in black spruce (*Picea mariana* [Mill.] B.S.P.) seedlings (Columbo and Glerum 1984), but that our understanding of the relationship between physiological status and new root growth is a limiting factor in the application of this test. RGP describes seedling performance potential, rather than performance, which is an important distinction, as field conditions are rarely optimal for seedling root growth. Folk and Grossnickle (1997) propose the use of limiting environmental conditions in RGP testing as a means to overcome this problem, whereby actual field conditions are simulated.

In addition to concerns over the applicability and accuracy of this method for evaluating seedling physiological status, RGP testing does not allow for rapid decision making by the grower since seedlings must be placed in the growing environment for at least 7 days (Sutton 1990; Sampson et al. 1997). Since RGP can fluctuate seasonally (Stone and Schubert 1959), results may no longer be applicable by the time the test is complete.

### *Electrolyte leakage*

Measurement of electrolyte leakage of plant tissue can serve as a quantitative assessment of seedling cold hardiness (Burr et al. 1990), dormancy status (Wilson and Jacobs 2004), and stress tolerance (McKay and White 1997), all of which are interrelated (Burr 1990), by estimating cell damage due to loss of cell membrane integrity. Though not commonly practiced, use of root electrolyte leakage as a quantitative measure of seedling dormancy status could be beneficial in assessing cold hardiness in seedlings. As seedling roots tend to be less cold-hardy than shoots (Smit-Spinks et al. 1985; Bigras and D'Aoust 1993; Bigras and Margolis 1997), it may sometimes be logical to assess seedling cold hardiness on these sensitive plant parts. Measurement of root electrolyte leakage may be an important factor in determining field performance, and therefore warrants inclusion as a measure of quality in situations where cold hardiness assessment must be rapidly quantified to ensure successful establishment.

McKay (1992) proposed the use of fine root (i.e., roots $\leq 2$ mm) electrolyte leakage as a rapid measure of seedling vitality following cold storage. In that study, electrolyte leakage served as a better predictor than RGP for survival and growth for Douglas-fir, Japanese larch (*Larix leptolepis* [Sieb. & Zucc.] Gord.), and Sitka spruce. McKay (1998) also found similar results for Sitka spruce, Japanese larch, and Scottish larch (*Larix eurolepis* Henry). Results of work to date, while generally showing positive results, have been somewhat inconsistent. For example, in a study assessing vigor of Austrian pine, root electrolyte leakage was a less efficient predictor than RGP (Chiatante et al. 2002). Furthermore, O'Reilly et al. (2002) found that root electrolyte leakage could not be used to predict field height growth in ash or sycamore (*Acer pseudoplatanus* L). On the contrary, root electrolyte leakage reliably predicted field survival of sycamore, flowering ash (*Fraxinus ornus* L.), and chestnut (*Castanea sativa* Mill.) (Radoglou and Raftoyannis 2001). Increased testing of this method will help to develop an acceptable use range, which will provide nursery growers with an understanding of situations in which this test is applicable.

### *Root carbohydrate content and nutrient storage*

Several studies suggest that root carbohydrate content, measured as root total non-structural carbohydrates (TNC), may be an indicator of seedling growth potential. Insufficient carbohydrate reserves during the period between lifting and the resumption of production of current photosynthate can result in a loss of vigor and, in extreme circumstances, mortality (Marshall 1985). Noland et al. (2001) found that the length of new roots of jack pine (*Pinus banksiana* Lamb.) seedlings was negatively correlated with root starch content, suggesting that carbohydrate reserves were depleted to support root initiation and extension. In a study of six hardwood species, root carbohydrate content increased with the onset of seedling dormancy (Farmer 1978). Root carbohydrate content may serve to predict seedling survival and growth in conditions where the ability to photosynthesize is limited immediately following outplanting. In a study with naturally regenerated seedlings of four hardwood species, Canham et al. (1999) found a positive relationship between seedling carbohydrate reserves and survival, with roots representing the dominant TNC storage site for all species. Seedling root carbohydrate content could be a useful indicator of seedling internal reserves. Furthermore, determination of a minimum root carbohydrate content (as TNC) for species prone to cycles of dieback and resprouting (i.e., *Quercus* spp.) could be especially useful in facilitating survival of these species.

In addition to carbohydrate content, nutrient storage in roots could be assessed as a further means of predicting seedling vigor. Inadequate reserves would likely result in poorer performance upon outplanting. Root reserve P accounted for up to 100% of the P required for shoot growth of coppice-grown flooded gum (*Eucalyptus grandis* Hill ex Maiden) (Ferreira Reis and Kimmins 1986). Furthermore, net re-translocation of N, P, and K from older plant tissues to new growth in black spruce seedlings was greatly improved by nutrient loading during nursery culture, indicating that translocation is driven by the magnitude of plant nutrient reserves (Salifu and Timmer 2001). Further research regarding the significance of root carbohydrate and nutrient reserves can help identify nursery cultural practices which tailor seedling reserves to a particular outplanting condition, resulting in improved root initiation and establishment.

### *Root moisture content*

Desiccation of root systems prior to outplanting can also negatively impact seedling establishment due to adverse impacts on root functions. Unprotected fine roots of two *Quercus* spp. were damaged during cold storage due to low water content (Genere et al. 2004). Damage to cell walls caused by desiccation could negatively impact seedling performance upon removal from cold storage. In a study of nine tree species, Radoglou and Raftoyannis (2002) found that seedling survival generally decreased at lower root moisture content levels. Comparatively, in a study of Douglas-fir seedlings, root moisture content measured at outplanting was considered to be a better predictor of survival and growth than root electrolyte leakage and pre-dawn shoot water potential (Genere and Garriou 1999). However, McKay and White (1997) found that root electrolyte leakage in Douglas-fir and Sitka spruce seedlings tended to be more frequently related to seedling performance than root moisture content. Contrasting results could be attributed to differences in application of testing methods or cultural and environmental conditions, further exemplifying the need for comparative testing of methods of quality assessment. Root moisture content may be more applicable to situations where seedlings are at risk of desiccation during storage, as Radoglou and Raftoyannis (2001) found that root moisture content was related to outplanting survival of sycamore, flowering ash, and chestnut only when seedlings were exposed to a desiccation treatment. Thus, in situations where risk of desiccation is not an issue, the usefulness of this test could be limited.

### *Physiological measurement of seedling root system quality*

Few studies have directly compared the relative effectiveness of the variety of tests available to assess seedling root system physiology. Thus, many questions associated with the current methods of physiological assessment of root system quality could be answered through continued testing across a broader range of species and environmental conditions. Standards could be established for minimum root carbohydrate, moisture, and nutrient content, for a particular species and stocktype. RGP testing under simulated field conditions will provide a means of more accurately predicting the likelihood of successful root initiation upon outplanting and, correspondingly, the true significance of this test as a measure of performance potential. Promising recent research into stress resistance through the analysis of electrolyte leakage will help create a better understanding of seedling dormancy and improve our ability to handle seedlings with minimal risk of damage. Furthermore, increased understanding of carbohydrate and nutrient reserves will provide a quantitative determination of the likelihood of successful new root initiation and growth upon outplanting.

It is unlikely that physiological evaluation will ever parallel morphological measurements of seedling quality in terms of applicability at an operational scale, and therefore better understanding of the relationships between physiological and morphological parameters could prove paramount to accurately predicting outplanting success. For example, where root carbohydrate content is found to be an important predictor of survival upon outplanting, the correlation between root volume and carbohydrate content may be worthy of further exploration.

## Synthesis and future directions

Many tools are available to assess the quality of seedling root systems; however, there is no single test which has proven suitable across a multitude of conditions and species. It is necessary that we increase our understanding of how these tools interact with species, the silvics associated with these species, and the environmental conditions expected at the time of plantation establishment. Testing the methods described above across a broader spectrum of species and site conditions will likely improve our understanding of the predictive nature of these tests. Root morphology (i.e., fibrosity, volume, length, area, the number of FOLR, or a combination of factors) can provide an important indicator of potential for water and nutrient uptake. While assessing root system quality is possible using the aforementioned methods, relation of the root system to the seedling shoot must also be considered to ensure proper balance in terms of potential for water loss through transpiration vs. water uptake through root absorption. Root:shoot, measured as dry weight or volume, has shown high capacity to predict field performance (Lopushinsky and Beebe 1976; Racey et al. 1983; Larsen et al. 1986; Jacobs et al. 2005). Root physiological status (i.e., RGP, electrolyte leakage, carbohydrate or moisture content, or nutrient status) could help further identify effects of specific nursery cultural techniques on seedling quality, as well as help guide appropriate lifting and outplanting dates.

Further development of new technologies, such as root scanning equipment, will lead to faster and more accurate non-destructive assessment of seedling root morphological quality (Rigney and Kranzler 1997; Bouma et al. 2000; Costa et al. 2001). Improved refinement of multiple-parameter models which include both root and shoot parameters will also enhance our ability to predict field success. While this concept is not new (i.e., Dickson et al. 1960), as our understanding of the relative importance of each parameter increases, these models should be adjusted accordingly. To this end, Levy and McKay (2003) found that sensitivity analysis could be used to quantify the relative importance of variation of parameters within a model. Explicit application of a model for a particular species intended for certain outplanting conditions is also necessary. For example, Jacobs et al. (2005) reported that models consisting of multiple morphological parameters were better predictors of seedling growth than single-parameter models for bareroot seedlings of three hardwood species in the Central Hardwood Forest Region, USA. In a study examining loblolly pine seedling survival, a model including the number of new roots ≥0.5 cm and root:shoot accounted for 80% of the variability in first-year survival (Larsen et al. 1986). Effective integration of both physiological and morphological parameters into future models may further benefit seedling root system quality evaluation. Furthermore, meta-analysis of presently available data from studies conducted on seedling growth and survival and the relationship to various parameters could also provide a clearer depiction of how to evaluate seedling root system quality.

The target seedling concept, described by Rose et al. (1990) as '*to target specific physiological and morphological seedling characteristics that can be quantitatively linked with reforestation success*', is an important tool used by foresters and nursery growers in improving seedling performance upon outplanting. Though no single test will be applicable to all situations, a better understanding of the efficacy of the tests described in this review will lead to more accurate incorporation of root system morphological parameters and physiological status into target seedling specifications, thereby improving our ability to predict seedling survival and growth after outplanting.

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