A review of root to shoot balance in containerized nursery tree stock: nature vs nursery.

COURTNEY E. CAMPANY1 and MARK G. TJOELKER1

1 Hawkesbury Institute for the Environment, Western Sydney University, Locked Bag 1797, Penrith 2751 NSW, Australia

## Trends in Australian tree nurseries: past and present

In 1997 the Australian federal government set a target to triple the nation’s plantation estate by 2020 with the ‘2020 Vision’ initiative (www.plantations2020.com.au). This initiative led a massive decade long expansion of plantations (>50 %) in Australia to over 2 million ha, with the majority of the increase composed of *Eucalyptus* hardwood species (Gavran & Parsons, 2010). This '2020 Vision' created a shift from bare root to containerized production of tree seedlings in nurseries to meet high volume demands of forestry companies (Close, 2012). During this period, it was necessary to increase emphasis on quality seedling testing to ensure containerized seedlings had characteristics that were favorable to out-planting in a wide range of planting sites (Close *et al.*, 2003). Recently, Horticulture Innovation Australia has introduced the new '202020 Vision' that aims to increase urban green space by 20% by the year 2020 (<http://202020vision.com.au>). This new initiative represents a significant market shift towards landscape use and introduces a new set of challenges to the Australian tree nursery industry for the foreseeable future.

These new challenges are highlighted by the difficulty in establishment and survival of newly planted urban trees (Nowak *et al.*, 2004; Miller *et al.*, 2015), and the pressure this places on individual nurseries to produce tree stock that can endure increasingly harsh environments. Hot and dry conditions in Australian cities, inconsistent irrigation, infertile soils, pests, diseases and high pressure from urban heat islands threaten the survivability of urban trees, and success of green infrastructure (HIA, 2016). Additionally, valuing trees to be selected for urban planting sometimes neglects considerations of stress endurance in favor of trees with higher aesthetic appeal (Ware, 1994; Pandit *et al.*, 2013). Consequently, Australian tree nurseries are now expected to provide a large array of native and non-native trees species that are all capable of enduring less than ideal out-planting site conditions.

As planting, establishment and monitoring of trees in urban environments requires considerable investment by local Councils (Lawry & Gardner, 2001), concerns over tree stock quality and out-planting success are inevitable. Selecting the appropriate cultivar, properly preparing the out-planting site and management of out-planted trees will be wasted if the quality of the planted seedling is initially poor (Moore, 2001). Confounding with the demands for diverse high quality trees is that variability within tree stock is a near certainty during nursery production. This variability presents a unique challenge for nurseries attempting to produce tree stock with uniform morphological characteristics (Puttonen, 1997).

## Assessing Seedling Quality

Evaluating nursery stock quality is necessary to understanding the capacity for growth and survival after out-planting (Wakeley, 1954), yet the quality of tree stock is often assessed inconsistently (Haase, 2008). Nursery stock should embody the structural and physiological traits that can be quantitatively linked to success in the field (Rose *et al.*, 1990). Nursery stock quality is a dynamic process that is the culmination of all the practices that have preceded the assessment (Mexal & Landis, 1990). A primary goal of quality assessments is to quantify attributes which accurately assess the condition and potential for growth of different nursery stock types (Wilson & Jacobs, 2006). As there is no single test which encompasses tree quality, assessing nursery stock is analogous to a physician conducting several measurements to characterize a patients general health (Ritchie, 1984).

Nursery stock quality is the basis for tree planting success and high quality trees will have a higher survival rate and faster growth in the field than poor quality trees (Wightman, 1999). Importantly, out-planting nursery stock with desirable plant attributes will not guarantee survival, but should increase survivability (Grossnickle, 2012). As tree stock are more acclimatized to nursery conditions than to planting site conditions, quality assessments inherently include some systematic error (Puttonen, 1997). Assessments during nursery production can also be problematic as tree stock characteristics often change during the high grow phase (Mattsson, 1997). Regardless, the ultimate goal of a generating a high quality tree stock is to ensure a very high percentage of out-planting establishment. Specifications for tree stock are designed to ensure that nursery stock can endure stresses from variable site conditions and growing climates, but are also applicable to a wide range to species and tree types.

## Grading tree stock morphology

Nursery tree stock can be graded by both morphological and physiological characteristics, and these characteristics should relate to out-planting performance (Landis, 2011). As cheap and quick physiological tests are lacking, morphological and physiological assessments are rarely conducted together (Hobbs, 1984; Pinto *et al.*, 2011a). Physiology and vigor of nursery tree stock can change significantly between production and out-planting, while morphology tends to stay the same (Pinto, 2011). As a result, non-destructive morphological measurements of tree stock form and structure are commonly used as indices of tree stock quality.

Measuring morphology in the nursery is now standard practice and has led to a classification system which correlates growth and survival with specific morphological traits (Ritchie, 1984; Pinto, 2011). The measured morphological attributes represent the cumulative series of physiological responses to both resources and stresses during nursery production (Mexal & Landis, 1990). Although the physiological condition of seedlings can override morphology, the size and shape of the plant still provides a beneficial tool for nurseries to grade tree stock and evaluate potential field survival and growth (Thompson, 1985). Thus, morphological attributes are considered a reliable measure of nursery stock quality as they retain their mark on the trees identity for extended time frames after out-planting (Puttonen, 1997; Grossnickle, 2012).

The main morphological attributes used to grade nursery tree stock quality are: height, diameter and root system size (Thompson, 1985; Mexal & Landis, 1990; Rose *et al.*, 1990; Haase, 2011; Pinto, 2011). The quality of an individual tree represents how each of these main attributes act together and influence one another (Wightman, 1999). Importantly, no single morphological factor has been shown to provide a perfect prediction of out-planting success, but many are linked with aspects of potential tree performance (Mattsson, 1997; Haase & Others, 2007). Of these, height and diameter are easily the two most common parameters examined in nursery tree stock, and minimum and maximum targets are usually established in grower specifications (Thompson, 1985; Haase, 2008). Assessments used to describe quality nursery stock generally convert these core morphological characteristics into grading standards (Landis & Dumroese, 2006).

### Aboveground

Metrics of shoot system size relate how available soil, water, nutrients and competition for light limited tree stock performance (Grossnickle, 2000). Height is considered a good estimate of photosynthetic capacity and transpirational area, suggesting a positive relationship with growth (Haase & Others, 2007). A quality tree should be as tall as possible while still possessing an acceptable level of survival potential for the designated site (Thompson, 1985). Larger tree height, however, can have adverse effects on field success in drier sites. This is because taller trees incur greater water loss by transpiration and tend to use more water, despite having greater leaf surface area for photosynthesis (Carlson & Miller, 1990). This has led to height being an inconsistent predictor of out-planting survival for nursery tree stock. Larger stock also adds difficulty in lifting, handling and planting properly, which can negate advantages of larger nursery tree stock in planting success (Cleary *et al.*, 1978).

Tree stock diameter is traditionally viewed as a index for sturdiness for nursery tree stock. Stem diameter increases concomitantly with height, but in tree nurseries this relationship is affected by growing density, fertility and pruning practices (Mexal & Landis, 1990). Positive relationships with diameter and root volume have also been reported for nursery trees (Dey & Parker, 1997; Jacobs & Seifert, 2004). As main stem diameter is easy to measure and is positive correlated with root system size (Cleary *et al.*, 1978, Wightman (1999)), it is an attractive parameter for nursery grading criteria (Dey & Parker, 1997). Diameter has also been shown to be positively related to total seedling mass and performance of out-planted seedlings for many nursery tree species (Thompson, 1985; Omi *et al.*, 1986; Aphalo & Rikala, 2003; South & Mitchell, 2006; Wilson & Jacobs, 2006; Zida *et al.*, 2008; Bayala *et al.*, 2009). In recent history the size of nursery tree container stock has been increasing, however, evidence that subsequent increases in stem diameter led to increased field performance is still lacking (South *et al.*, 2005).

### Belowground

Root system parameters are some of the best features to characterize tree stock quality (Wrzesiński, 2015), yet these parameters remain difficult to monitor during nursery production. Recently out-planted tree stock will initially depend on the root system created during nursery production (Grossnickle, 2005), thus enhancing the potential for root proliferation following transplanting will improve field establishment (Davis & Jacobs, 2005). The original root system size determines the ability to take up water to initiate the establishment process (Carlson & Miller, 1990; Wrzesiński, 2015), and establishment is dependent on the capacity of tree stock to rapidly initiate new roots (Heiskanen & Rikala, 1998, Grossnickle (2005)). This means that root quality parameters including rootball size, depth and container occupancy are commonly monitored to promote high out-planting success.

In nursery tree stock, root volume has been shown to be positively correlated with total mass, diameter, and tree height after out-planting (Rose *et al.*, 1991; Jacobs & Seifert, 2004; Jacobs *et al.*, 2005). The size of the root system, in terms of rooting volume, also likely determines the potential for water uptake prior to new root growth (Carlson, 1986). Root volume may not reflect root fibrosity, however, as tree stock with large fine root mass can displace the same volume as a seedlings with large tap roots (Haase & Others, 2007). Thus, it is important for the root system to fully colonize the container and contain actively growing roots tips. Seedlings with large numbers of active root tips have more sites for mycorrhizal development and thus increased nutrient uptake and growth in the nursery (Wilcox, 1968; Marx & Barnett, 1974; Mitchell *et al.*, 1984). Assessing root system quality, however, may be affected by variation in root morphology across species and nursery-specific root management practices.

Root form can be permanently altered if early stage root systems are disturbed, sometimes with detrimental effects (Thompson, 1985). A potential issue with larger container volume tree stock is that trees are subject to root spiraling and binding, which can negatively affect out-planting performance for years (Cleary *et al.*, 1978). Root spiraling has the potential to girdle the tree over time as they restrict the flow of water through the root-crown area (Moore, 2001). If left too long, root systems become bound with disproportionate large thick roots and dense root mats at the bottom of the rootball (Ford, 2014). Root binding occurs when a plant has roots too large for its container resulting in a reduction in field performance or root growth potential, which is a constant concern for tree nurseries (South & Mitchell, 2006). J-rooting also occurs when a seedling is improperly planted into container growing media and can manifest into a source of structural weakness at the soil interface as the tree grows (Moore, 2001). As new roots regenerate from the original out-planted root system, it is vital to assess root distribution patterns during nursery production (Watson & Himelick, 1982).

### Pitfalls of morphological assessments

Issues with using only morphological assessments, especially single parameter estimates of tree stock quality, have long been recognized to exhibit large variation. Use of simple morphological variables to predict absolute growth often fails to explain large proportions of variation in growth of out-planted trees (Pinto *et al.*, 2011b). For example, Wakeley (1954) first noted how morphological assessments of root collar diameter and height led to unreliable grades of survival and growth in long-leaf and slash pine seedlings. Measurements of root system morphology are also destructive and time consuming, limiting their application in production nurseries (Jacobs & Seifert, 2004). Although morphological parameters can assess seedling size, growth potential and shoot to root balance; they may also not accurately capture seedling physiological quality (Mexal & Landis, 1990, Grossnickle (2012)). Unfavorable morphological grades of tree stock may therefore occur, without actually inferring different capacities for field success. Although this issue represents a fundamental problem for the nursery industry, morphological indices still represent the most cost-effective standard practice.

### Building quantitaive links between morphological parameters

The realization that no single factor predicts out-planting success led to the 'target seedling concept' by Rose *et al.* (1990), which proposes that numerous physiological and morphological traits should be tracked and developed to quantitatively assess nursery stock performance (Rose & Hasse, 1995). Global adaptation of this concept has led to a suite of quality assessment criteria that are now essential elements in quality testing protocols. It is commonly accepted that height and diameter measurements alone do not always correlate with seedling performance following out-planting. As height, stem diameter and shoot-root ratio each influence seedling tolerance to environmental stresses, they should be considered in relation to each other (Cleary *et al.*, 1978). Indices combining various morphological traits (e.g. root:shoot, height:diameter) have now been adopted to more accurately assess overall nursery tree stock quality.

As grading standards of single morphological parameters may not capture inherent variation in tree stock, they may lead to culling of stock that are capable of surviving at a high rate. Multiple regression models have been shown to better predict tree stock quality than with single parameters (Jacobs *et al.*, 2005). Consequently, morphological indexes combining multiple morphological measurements better correlate to beneficial tree stock attributes and performance (Thompson, 1985). Morphological indexes generally separate into 2 categories, those that describe aspects of the aboveground architecture of plant, and those that combine above- and belowground parameters to assess the balance between shoots and roots.

A common aboveground index is tree slenderness, calculated as the height:diameter ratio, which is indicative of a plants taper and reflects an ability to withstand physical damage (Peterson, 1997). When slenderness is too high plants have decreasing stability in the field, and the root system may be insufficient to support the shoot biomass under drought type planting conditions (Haase & Others, 2007; Ford, 2014). The slenderness index was correlated with mortality in Patula pine, suggesting it may serve as a good indices of survival (Bayley & Kietzka, 1997), however, is was not related to field performance in Silver Birch (Aphalo & Rikala, 2003). This disagreement likely arises from focusing only on aboveground grading criteria, which ignores the importance of root system morphology in growth and field survival (Schultz *et al.*, 1990). Although easy and cost effective to measure, aboveground indexes are insufficient to capture the overall balance of nursery tree stock.

## Root to shoot balance in nursery tree stock

To become established, a transplanted nursery tree must generate a root system to support shoot growth that is comparable to a non-transplanted tree (Watson *et al.*, 1997). The challenge facing nursery growers is to optimize canopy growth while also ensuring that root systems are properly managed, especially as containerized systems can alter root system quality (Moore, 2001). From a structural point of view, the root and shoot system should be balanced to ensure the stability of the seedling during production and when out-planted. To prevent toppling, the shoot not be too tall relative to the stem diameter and the shoot mass not too large relative to the roots (Haase, 2008). To be self-supporting, the root system should also be of sufficient size to anchor the tree. Imbalances above and belowground can put larger sized tree stock at higher risk of transplant shock (Rietveld, 1989; South & Zwolinski, 1997).

Proper root:shoot balance is also an essential morphological attribute because it is an index of plant water uptake capacity (root) to water loss (shoot) at the time of planting (Ritchie, 1984; Thompson, 1985; Grossnickle, 2000; Haase & Others, 2007). Higher root:shoot ratios may result in more favorable water relations, lower shoot maintenance requirements and faster growth rates (Close *et al.*, 2010), although this does not always translate into reduced water stress post-planting (Lamhamed *et al.*, 1997). An overly large shoot mass can decrease survival as evaporative surface exceeds water uptake capacity, while a too small shoot mass impacts drought survival by the inability to photosynthesize necessary carbohydrate reserves (Cregg, 1994). An underdeveloped root system size may also decouple the tree from available soil water and negatively affect seedling nutrient uptake when planted (Grossnickle, 2005). Consequently, combinations of root and shoot morphological characteristics may better assess nursery tree stock quality and predict future health.

## Impact of nursery practices on tree stock balance

Nursery practices have a large influence on tree stock performance immediately after planting (Grossnickle, 2012). The degree of variation detected in quality assessments of root and shoot morphology may largely depend on nursery-specific growing practices. For example, improper nursery management may encourage a disproportionate amount of shoot growth, resulting in unbalanced tree stock with lower field-survival potential (Cleary *et al.*, 1978). Below we review aspects of common nursery practices that feedback to overall root to shoot balance of nursery tree stock.

### 1. Containerized vs bare root tree stock

Containerized trees stock possess complete root systems oriented downward, with at least one in a position to become a taproot (McDonald, 1991). Alternatively, bareroot trees are grown in open field nurseries, harvested and the soil is removed from the root system (Grossnickle & El-Kassaby, 2015). Containerized seedlings have been generally shown to have greater survival percentage over bare-root seedlings (South *et al.*, 2005), including higher field survival in sites with drought conditions (Grossnickle, 2005 and references therein). This increased survival is attributed to containerized tree stock being easier to plant and having more immediate growth response benefits than bare-root trees (Landis *et al.*, 1990). Although bare-root and container stock types have distinct characteristics influencing their field survival, new nursery practices are developing bare-root seedlings with more balanced root to shoot systems (Grossnickle & El-Kassaby, 2015). Current international nursery standards now regulate the size of the bare-root seedling rootball removed in relation to the size of the tree aboveground (see AmericanHort, 2014; The British Standards Institution, 2014). Fundamental differences between these two stock types are important for nursery decision making, as optimal quality specifications need still apply to both (Aphalo & Rikala, 2003).

Bare root trees have larger shoot systems than containerized trees because they are typically grown for longer and at lower densities (Grossnickle & El-Kassaby, 2015). The root systems of bare-root seedlings are disrupted in the process of lifting, while containerized seedlings typically maintain intact multidimensional root system and have greater root growth after out-planting (Tinus, 1974; Johnson *et al.*, 1984; Rose & Haase, 2005; Wilson *et al.*, 2007). The removal procedure for bare-root trees initially produces an imbalance in the root:shoot ratio, with harvested bareroot trees generally having root:shoot ratio of 1:3 compared to containerized tree with a root:shoot ratio 1:2 (Schultz *et al.*, 1990; Haase & Others, 2007). Deciduous bare root trees, however, are often planted into containers to produce larger size trees for landscape use. The degree to which the initial inherent differences in harvested bare root trees affect subsequent growth, balance and quality during containerized production remains unknown.

### 2. Container type

The container design used for nursery tree stock has a major influence on root systems (Landis *et al.*, 1990, Chapman & Colombo (2006)) and plants grown in containers generally have a different root morphology than field-grown plants (NeSmith & Duval, 1998). Trees grown in containers have been shown to develop root deformations (Ortega *et al.*, 2006), thus it is common practice to actively manage root systems during containerized nursery production. There are numerous container types and treatments applied to containers aimed at root pruning and manipulating root direction and division. For example, air or mechanical pruning containers and copper compounds applied to interior container surfaces are utilized to decrease root deflection. Container types designed to aid root pruning should produce seedlings with horizontally orientated structural roots and more stable root forms (Chapman & Colombo, 2006). Although roots deflected inside containers are commonly associated with tree instability, little is still known about root form in large size nursery containers (Gilman *et al.*, 2010).

Containers that auto-prune roots may inadvertently alter natural patterns of tree biomass investment (Climent *et al.*, 2008), affecting root to shoot balance during nursery production. Height and diameter of red maple seedlings were similar across a range of container types after 24 weeks, however, root deflection was decreased in containers with air or chemically pruned roots compared to standard plastic containers (Marshall & Gilman, 1998). Alternatively, shoot biomass of *Tilia cordata* was lower in air-pruning containers after two seasons compared to smooth sided or ribbed containers, while root biomass was unaffected (Amoroso *et al.*, 2010). Future work is still needed to determine how root to shoot balance is affected by the variety of available auto-pruning container types, especially for larger containers with longer production times.

### 3. Active root pruning

Plants grown in common smooth-sided containers can have the higher percentages of deformed roots (Amoroso *et al.*, 2010), thus nurseries often actively root prune containerized tree stock. Root pruning can vastly increase the surface area of the root system and increase the amount of roots within the root ball if properly managed (Watson & Sydnor, 1987, Gilman & Beeson (1996)). Pruning the rootball allows for roots to grow radially straight from the trunk when planted into larger containers, decreasing root morphological defects (e.g. kinks, j-rooting) (Gilman *et al.*, 2010). Tree stability and out-planting establishment also improves when root defects are reduced from active root pruning (Gouin, 1983; Gilman *et al.*, 2009). Proper root-pruning can allow any shape of container to produce a plant with the potential to develop a natural root form (Nelson, 1996).

In the absence of any root pruning management, either manually or by container type, root binding and root restriction is likely to occur. Container root restriction can alter root morphology, affecting the ability to absorb water and causing symptoms of water stress in plants, even under well-watered conditions (Krizek *et al.*, 1985). Root:shoot ratios can be confounded in quality assessments when low values do not reflect a thick taproot system instead of a large fibrous root system, which offers limited surface area for water uptake (Ambebe *et al.*, 2013). Additionally, roots undergoing difficult conditions may send inhibitory signals to shoots that inhibit leaf physiology and growth (Passioura, 2002). Active management of root pruning can alleviate these negative feedbacks to physiology, growth and tree balance, which should be prioritized to improve tree stock quality during nursery production.

### 4. Container volume

Volume is one of the most obvious and important characteristics of a containerized production, however, optimum container sizes can vary by species, growing density, environmental conditions and growing season length (Tsakaldimi *et al.*, 2005). A review of the pot size effect on woody species found that increasing container volume generally increases biomass production (Poorter *et al.*, 2012). For nurseries, larger volume containers require more medium, fertilizer, and space than smaller containers, which increases production cost (Bowden, 1993). Across a longer timescale, however, it may be more economical to purchase and plant an expensive tree with a higher rate of survival that a less expensive tree with a higher mortality rate (Miller *et al.*, 2015). How overall tree balance and subsequent field performance are altered by growing stock in larger containers represents a fundamental question that intersects seedling quality and economics during nursery production.

The use of different containers volumes has been shown to have morphological consequences for tree stock both above and belowground. Container volumes that are too small exert serious constraints on the growth and function of roots, especially in hardwood species (Wilson *et al.*, 2007; Mariotti *et al.*, 2015). Root restriction inhibits the ability of root system to supply water, negatively affects physiological activity and mechanically impedes whole plant growth, regardless of growing media, watering or fertilization (McConnaughay & Bazzaz, 1991; Will & Teskey, 1997; Climent *et al.*, 2011). Alternatively, positive associations with height, caliper and total mass are often observed with increasing container size (Ran *et al.*, 1992; Hsu *et al.*, 1996; Peterson, 1997; Mariotti *et al.*, 2015). Increased container depth also improves root system growth and tap root length, which aids in soil colonization when out-planted (Chirino *et al.*, 2008). The degree of these effects of rooting volume are likely to differ according to species grow rates (Climent *et al.*, 2011), which is especially relevant for production nurseries that produce a large variety of tree species.

The increasing demand for larger size trees for landscape projects now dictates that a large range of container volumes be used in nursery production. Growing tree stock in large volume containers may result in natural shifts of root to shoot balance related to age and development as trees grow larger. However, the majority of existing research investigating the impacts of container volume on tree balance and growth is concentrated on trees grown for reforestation and plantation purposes. This has led to a large knowledge gap, as the typical range of container sizes used for these purposes (<1 L) is massively smaller than containers now used for nursery trees for landscape use (>1000L). Increases, decrease and no effect of container volume on root:shoot ratios have been observed across many species from forestry related studies (Carlson & Endean, 1976; Aphalo & Rikala, 2003; Close *et al.*, 2003, 2010; Climent *et al.*, 2011; Mariotti *et al.*, 2015), yet the maximum container size for any of these studies was < 20L. Future work is needed to test if above and belowground balance of tree species grown for landscape use is altered by container size, especially larger volumes.

### 5. Irrigation, fertilization and growing media

Nursery tree production requires the use of large quantities of water (Bumgarner *et al.*, 2008), yet conventional irrigation scheduling is often based on observations and experience instead of actual plant water status (Tran, 2016). Maintaining favorable moisture conditions in the rooting medium of seedlings is a critical factor in the nursery tree production (Timmer & Armstrong, 1989). Over-irrigating can led to reduced growth during nursery production (Bergeron *et al.*, 2004), likely a consequence of reduced soil aeration and impeded root development (Heiskanen, 1993). However, above and belowground responses to varying irrigation regimes differ by species, container type and irrigation method (Timmer & Armstrong, 1989; Lamhamedi *et al.*, 2001; Royo *et al.*, 2001; Stowe *et al.*, 2001; Bergeron *et al.*, 2004; Bumgarner *et al.*, 2008; Davis *et al.*, 2008). Alternatively, drought hardening regimes can also be applied during nursery production to increase drought tolerance before out-planting into dry sites (Villar-Salvador *et al.*, 2004b).

Within nursery environments, maximum shoot growth occurs at high soil water regimes and moderate to high fertility levels (Mexal & Landis, 1990). Increasing the amount of applied fertilization increases the dry weight of both the shoots and the roots (Brissette, 1990), while enhancing the capacity of new root formation (Villar-Salvador *et al.*, 2004a). Fertilization tends to stimulate shoot growth more than root growth by reducing belowground resource limitation (McConnaughay & Bazzaz, 1991; Canham *et al.*, 1996; Villar-Salvador *et al.*, 2004a; Bumgarner *et al.*, 2008; Luis *et al.*, 2009; Jackson *et al.*, 2012). If not properly managed, nutrient deficiencies in nursery trees can also cause negative impacts on leaf physiology, carbohydrate production, height and diameter (Trubat *et al.*, 2010). Overall, tree balance of nursery tree stock can be significantly altered or specifically managed through fertilization regimes. Fertilization regimes also feedback to out-planting success as alleviation of nitrogen stress may decrease carbon allocated to storage (Green *et al.*, 1994; Holopainen *et al.*, 1995) or nitrogen hardening may improve field performance in semi-arid or droughted planting sites (Villar-Salvador *et al.*, 2004a; Trubat *et al.*, 2008, 2011).

Growing media (potting soil) must be porous enough to provide efficient exchange of oxygen and carbon dioxide, while also having a sufficient water holding capacity to supply water to the plant (Landis *et al.*, 1990; Heiskanen, 1993). The use of different growing media, to control soil structure, nutrition, pH, moisture, temperature, and aeration, can be used to manage root development (Heiskanen & Rikala, 1998; Kazantseva *et al.*, 2009). Choice of growing media can also impact the nutrient status of soil, which then feedbacks to both root and shoot growth. For example, improved aeration may stimulate microbiological activity and decomposition of organic matter, thus increasing nutrient availability for containerized seedlings (Wall & Heiskanen, 2003). Management strategies for nursery stock must also be mindful of trees destined for harsh urban environments, which may include the use of more skeletal soils during nursery production (Loh *et al.*, 2003). Overall, fertilization, irrigation and growing media interact during containerized tree production to influence resource availability and the subsequent growth of both root and shoots.

# Impact of climate on nursery tree stock

Different environmental conditions can have important influences on functional traits of different nursery tree stock (Mollá *et al.*, 2006), which is importance when designing nursery quality assessment criteria for broad geographic regions. Consequently, tree stock grading may differ among similar species from different nurseries, even when they are produced from the same seed source and over the same growing season (Pinto *et al.*, 2011a). Existing research on the impacts of climate on nursery tree stock focuses heavily on growing season cycles of deciduous tree stock or comparisons of coastal versus inland nursery locations in Mediterranean climates. For example, shoot and root growth, frost resistance and drought tolerance were related to winter climate conditions at different nursery locations for several Mediterranean species (Pardos *et al.*, 2003 Mollá *et al.* (2006)). Although informative, this research does not address the impacts of climate on the large diversity of tree stock grown for urban and landscape projects. The potential impact of climate on nursery tree growth in Australia has been largely unexplored, where nurseries propagate trees from tropical to temperate climates.

Due to the large size of the Australian continent, six different climatic zones exists with two distinct seasonal patterns (Figure 1), thus geographic location of a nursery may play a key role in differences between growth and balance of similar tree stock types. Importantly, most production nurseries in Australia grow containerized trees in open air environments. As tree stock growth is heavily influenced by levels of moisture, temperature, light (Cleary *et al.*, 1978), open-air tree stock are likely to face vastly different environmental conditions according to the prevailing climate at each nursery location. Providing water is adequate, large growth responses of nursery trees are found with changes in temperature and the intensity, quality, and duration of light (Callaham, 1962). For example, diameter growth of different native eucalpyt species is related to prevailing air temperature (Bowman *et al.*, 2014), which varies tremendously across continental Australia. The degree to which the above and belowground morphological parameters related to tree balance are altered by differing growing climates remains largely unexplored for tree production nurseries.

## Using tree balance to mitigate transplant stock

The three primary types of stress that influence seedling quality are moisture, temperature, and physical stress.(Haase & Others, 2007). Nursery trees can be profoundly impacted by each of these stresses during nursery production, including culturing, lifting, packing, grading, handling, pruning, storage, and transport. Out-planted trees also endure varying degrees of these stresses from the environment, which determines the length and severity of 'transplant shock'. Transplant shock represents the negative effects on growth and survival when nursery-raised stock are out-planted and is associated with acclimatization of plants to a new environment (Close *et al.*, 2005). It takes longer for larger transplanted trees to becomes established due to the longer time required to reestablish a root:shoot ratio comparable to non-transplanted trees (Watson, 2005).

Out-planting success depends on the interactions between tree stock attributes and the environmental conditions of the site, with high quality morphological/physiological attributes especially important under harsh field conditions (Stape *et al.*, 2001). To overcome transplant stress after planting the root system must meet the transpiration demands of the shoot system (Grossnickle, 2005; Ford, 2014). Consequently, reductions in stress can be actively managed with nursery practices that achieve proper above and belowground balance of tree stock. Planned increases in urban green spaces, combined with varying climate and soil constraints that typically define Australian ecosystems, make minimizing transplant shock a highly relevant issue for tree stock for landscape use. Consequently, proper tree balance criteria are now specified in quality assessments of Australian tree stock (Clark, 2003; Standards Australia Limited, 2015).

# Future Directions

The issue of a lack of standardized method for determining root:shoot balance in nursery plants raised by Lavender (1984) still exists today. Quality assessments for nursery tree stock generally focus on 3 core parameters (height, diameter and root system size) to assess tree stock balance, albeit in different ways. Estimates of the size of a tree aboveground are commonly generated in forestry research using the relationship between tree height and diameter (Zianis *et al.*, 2005; Picard *et al.*, 2012; Hulshof *et al.*, 2015). The relationship between diameter and height represents stem formation in order to resist buckling related to weight or wind forcing (Dean & Long, 1986). This is advantageous to the nursery industry as these two measurements are commonly utilized morphological characterizations of seedling quality, and can provide a method to assess the aboveground bulk of a nursery tree at any given time (Clark, 2003). However, it is difficult to determine a quantity of roots that should exist for individual tree stock (Thompson, 1985). Root volume does provides a simple characterization of root system morphology (Jacobs *et al.*, 2005). However, actual measurements of root volume are not practical or cost effective for nurseries and container volume must often be used as a surrogate.

A question also still remains over whether quality assessment criteria, including single morphological parameters or indexes, accurately encompass inherent variation that exists across tree species. Although plants use all the same resources for growth; the construction, lifespan and relative allocation of leaves, stems, and roots vary between species (Westoby *et al.*, 2002). Large differences in growth rates exists across species or plant functional types, which plays a critical role in how different tree stock develop within nursery environments. Differences in growth rates are linked to the habitat for which a species naturally occurs, such as fast-growing trees are found in favorable habitats that support growth or trees from nutrient-poor environments are often evergreens with higher leaf longevity (Poorter & Garnier, 1999). Given this variation in plant form, generalized metrics to assess tree stock quality may not be all suitable across different tree species without large inherent error.

Depending on container size and type, there is an age window where plants exhibit optimum physiology and size, eliminating issues with low rootball occupancy or being too old with defected root systems (Ford, 2014). This optimum window represents the time period for which a given tree stock is fit to be sold and when quality assessments are commonly conducted. However, this window is likely different for species with different growth rates, functional types (deciduous or evergreen trees), or species origins (native/non-native). Additionally, prevailing climate and different irrigation and fertilization regimes across nursery sites impact tree stock quality during production (Mattsson, 1997). As information is gained from local nurseries, specifications for containerized plants are likely to change to more accurately match site, species, and planting time to individual stock types (Nelson, 1996). If superior morphological predictors can be identified it may be possible to modify nursery cultural techniques to improve quality (Wilson & Jacobs, 2006). Quality assessment specifications for nursery tree stock balance remain challenging to develop and implement, yet they are crucial for ensuring the success of future landscape and urban infrastructure projects.

# References

Ambebe TF**,** Fontem LA**,** Azibo BR**,** Mogho NMT. **2013**. Evaluation of regeneration stock alternatives for optimization of growth and survival of field-grown forest trees. *Journal of Life Sciences* **7**: 507–516.

AmericanHort. **2014**. *American standard for nursery stock*. Columbus, Ohio, USA.

Amoroso G**,** Frangi P**,** Piatti R**,** Ferrini F**,** Fini A**,** Faoro M. **2010**. Effect of container design on plant growth and root deformation of littleleaf linden and field elm. *HortScience* **45**: 1824–1829.

Aphalo P**,** Rikala R. **2003**. Field performance of silver-birch planting-stock grown at different spacing and in containers of different volume. *New Forests* **25**: 93–108.

Bayala J**,** Dianda M**,** Wilson J**,** Ouedraogo SJ**,** Sanon K. **2009**. Predicting field performance of five irrigated tree species using seedling quality assessment in Burkina Faso, West Africa. *New Forests* **38**: 309–322.

Bayley AD**,** Kietzka JW. **1997**. Stock quality and field performance of *Pinus patula* seedlings produced under two nursery growing regimes during seven different nursery production periods. *New Forests* **13**: 341–356.

Bergeron O**,** Lamhamedi MS**,** Margolis HA**,** Bernier PY**,** Stowe DC. **2004**. Irrigation control and physiological responses of nursery-grown black spruce seedlings (1+ 0) cultivated in air-slit containers. *HortScience* **39**: 599–605.

Bowden R. **1993**. Stock type selection in british columbia. Proceedings of the 1993 forest nursery association of British Columbia meeting. Forest Nursery Association of British Columbia.17–20.

Bowman DM**,** Williamson GJ**,** Keenan R**,** Prior LD. **2014**. A warmer world will reduce tree growth in evergreen broadleaf forests: evidence from Australian temperate and subtropical eucalypt forests. *Global Ecology and Biogeography* **23**: 925–934.

Brissette JC. **1990**. *Development and function of the root systems of southern pine nursery stock*. Southern Forest Experiment Station.

Bumgarner ML**,** Salifu KF**,** Jacobs DF. **2008**. Subirrigation of *quercus rubra* seedlings: Nursery stock quality, media chemistry, and early field performance. *HortScience* **43**: 2179–2185.

Callaham RZ. **1962**. Geographic variability in growth of forest trees. In: Kozlowski TT, ed. Tree growth. New York: Ronald Press Company, 311–325.

Canham CD**,** Berkowitz AR**,** Kelly VR**,** Lovett GM**,** Ollinger SV**,** Schnurr J. **1996**. Biomass allocation and multiple resource limitation in tree seedlings. *Canadian Journal of Forest Research* **26**: 1521–1530.

Carlson WC. **1986**. Root system considerations in the quality of loblolly pine seedlings. *Southern Journal of Applied Forestry* **10**: 87–92.

Carlson LW**,** Endean F. **1976**. The effect of rooting volume and container configuration on the early growth of white spruce seedlings. *Canadian Journal of Forest Research* **6**: 221–224.

Carlson WC**,** Miller DE. **1990**. Target seedling root system size, hydraulic conductivity, and water use during seedling establishment. *In: Proceedings, Western Forest Nursery Association, Roseburg, OR. General technical report RM-200, US Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, Fort Collins, CO*: 53–65.

Chapman KA**,** Colombo SJ. **2006**. Early root morphology of jack pine seedlings grown in different types of container. *Scandinavian Journal of Forest Research* **21**: 372–379.

Chirino E**,** Vilagrosa A**,** Hernández EI**,** Matos A**,** Vallejo VR. **2008**. Effects of a deep container on morpho-functional characteristics and root colonization in *Quercus suber* L. seedlings for reforestation in Mediterranean climate. *Forest Ecology and Management* **256**: 779–785.

Clark R. **2003**. *Specifying trees: a guide to assessment of tree quality*. Sydney, Australia: NATSPEC/Construction Information.

Cleary BD**,** Greaves RD**,** Owsten PW. **1978**. *Seedlings* (BD Cleary, RD Greaves, and RK Hermann, Eds.). Corvallis, OR, Corvallis, Or.: Oregon State University Extension Service; Oregon State University Extension Service.

Climent J**,** Alonso J**,** Gil L. **2008**. Short Note: Root restriction hindered early allometric differentiation between seedlings of two provenances of Canary Island pine. *Silvae Genetica* **57**: 187.

Climent J**,** Chambel MR**,** Pardos M**,** Lario F**,** Villar-Salvador P. **2011**. Biomass allocation and foliage heteroblasty in hard pine species respond differentially to reduction in rooting volume. *European Journal of Forest Research* **130**: 841–850.

Close DC. **2012**. A review of ecophysiologically-based seedling specifications for temperate Australian eucalypt plantations. *New Forests* **43**: 739–753.

Close DC**,** Bail I**,** Beadle CL**,** Clasen QC. **2003**. Physical and nutritional characteristics and performance after planting of *Eucalyptus globulus* Labill. seedlings from ten nurseries: implications for seedling specifications. *Australian Forestry* **66**: 145–152.

Close DC**,** Beadle CL**,** Brown PH. **2005**. The physiological basis of containerised tree seedling ‘transplant shock’: a review. *Australian Forestry* **68**: 112–120.

Close DC**,** Paterson S**,** Corkrey R**,** McArthur C. **2010**. Influences of seedling size, container type and mammal browsing on the establishment of *Eucalyptus globulus* in plantation forestry. *New Forests* **39**: 105–115.

Cregg BM. **1994**. Carbon allocation, gas exchange, and needle morphology of *Pinus ponderosa* genotypes known to differ in growth and survival under imposed drought. *Tree Physiology* **14**: 883–898.

Davis AS**,** Jacobs DF. **2005**. Quantifying root system quality of nursery seedlings and relationship to outplanting performance. *New Forests* **30**: 295–311.

Davis AS**,** Jacobs DF**,** Overton RP**,** Dumroese RK. **2008**. Influence of irrigation method and container type on northern red oak seedling growth and media electrical conductivity. *Native Plants Journal* **9**: 4–12.

Dean T**,** Long JN. **1986**. Validity of constant-stress and elastic-instability principles of stem formation in *pinus contorta* and *trifolium pratense*. *Annals of Botany* **58**: 833–840.

Dey DC**,** Parker WC. **1997**. Morphological indicators of stock quality and field performance of red oak (*Quercus rubra* L.) seedlings underplanted in a central Ontario shelterwood. *New Forests* **14**: 145–156.

Ford C. **2014**. Improving field survival of pine seedlings and cuttings: the Sappi Plant Quality Index. *Proceedings of the International Plant Propagator’s Society-2013*: 11–16.

Gavran M**,** Parsons M. **2010**. *Australia’s plantations 2010 Inventory Update*. Canberra: National Forest Inventory, Bureau of Rural Sciences.

Gilman EF**,** Beeson RC. **1996**. Nursery production method affects root growth. *Journal of Environmental Horticulture* **14**: 88–90.

Gilman EF**,** Harchick C**,** Wiese C**,** Others. **2009**. Pruning roots affects tree quality in container-grown oaks. *Journal of Environmental Horticulture* **27**: 7–11.

Gilman EF**,** Paz M**,** Harchick C. **2010**. Root ball shaving improves root systems on seven tree species in containers. *Journal of Environmental Horticulture* **28**: 13.

Gouin FR. **1983**. Girdling by roots and ropes. *Journal of Environmental Horticulture* **1**: 48–50.

Green TH**,** Mitchell RJ**,** Gjerstad DH. **1994**. Effects of nitrogen on the response of loblolly pine to drought. *New Phytologist* **128**: 145–152.

Grossnickle SC. **2000**. *Ecophysiology of northern spruce species*. Ottawa, Ontario, Canada: NRC Research Press.

Grossnickle SC. **2005**. Importance of root growth in overcoming planting stress. *New Forests* **30**: 273–294.

Grossnickle SC. **2012**. Why seedlings survive: influence of plant attributes. *New Forests* **43**: 711–738.

Grossnickle SC**,** El-Kassaby YA. **2015**. Bareroot versus container stocktypes: a performance comparison. *New Forests*: 1–51.

Haase DL. **2008**. Understanding forest seedling quality: measurements and interpretation. *Tree Planters’ Notes* **52**: 24–30.

Haase DL. **2011**. Seedling root targets. *National proceedings: Forest and Conservation Nursery Associations-2010*.

Haase DL**,** Others. **2007**. Morphological and physiological evaluations of seedling quality. *National proceedings: Forest and Conservation Nursery Associations-2006. Proc. RMRS-P-50. Fort Collins, CO: US Department of Agriculture, Forest Service, Rocky Mountain Research Station*: 3–8.

Heiskanen J. **1993**. Favourable water and aeration conditions for growth media used in containerized tree seedling production: A review. *Scandinavian Journal of Forest Research* **8**: 337–358.

Heiskanen J**,** Rikala R. **1998**. Influence of different nursery container media on rooting of Scots pine and silver birch seedlings after transplanting. *New Forests* **16**: 27–42.

HIA. **2016**. Horticulture Innovation Australia.

Hobbs SD. **1984**. The influence of species and stocktype selection on stand establishment: an ecophysiological perspective. In: Duryea ML, In: Brown GN, eds. Seedling physiology and reforestation success. Netherlands: Springer, 179–224.

Holopainen JK**,** Rikala R**,** Kainulainen P**,** Oksanen J. **1995**. Resource partitioning to growth, storage and defence in nitrogen-fertilized Scots pine and susceptibility of the seedlings to the tarnished plant bug Lygus rugulipennis. *New Phytologist* **131**: 521–532.

Hsu YM**,** Tseng MJ**,** Lin CH. **1996**. Container volume affects growth and development of wax-apple. *HortScience* **31**: 1139–1142.

Hulshof CM**,** Swenson NG**,** Weiser MD. **2015**. Tree height–diameter allometry across the united states. *Ecology and Evolution* **5**: 1193–1204.

Jackson DP**,** Dumroese RK**,** Barnett JP. **2012**. Nursery response of container *Pinus palustris* seedlings to nitrogen supply and subsequent effects on outplanting performance. *Forest Ecology and Management* **265**: 1–12.

Jacobs DF**,** Seifert JR. **2004**. Re-evaluating the significance of the first-order lateral root grading criterion for hardwood seedlings. Proceedings of the Fourteenth Central Hardwood Forest Conference. Wooster, Ohio.17–19.

Jacobs DF**,** Salifu KF**,** Seifert JR. **2005**. Relative contribution of initial root and shoot morphology in predicting field performance of hardwood seedlings. *New Forests* **30**: 235–251.

Johnson PS**,** Novinger SL**,** Mares WG. **1984**. Root, shoot, and leaf area growth potentials of northern red oak planting stock. *Forest Science* **30**: 1017–1026.

Kazantseva O**,** Bingham M**,** Simard SW**,** Berch SM. **2009**. Effects of growth medium, nutrients, water, and aeration on mycorrhization and biomass allocation of greenhouse-grown interior douglas-fir seedlings. *Mycorrhiza* **20**: 51–66.

Krizek DT**,** Carmi A**,** Mirecki RM**,** SNYDER FW**,** BUNCE JA. **1985**. Comparative effects of soil moisture stress and restricted root zone volume on morphogenetic and physiological responses of soybean [*Glycine max* (L.) Merr.]. *Journal of Experimental Botany* **36**: 25–38.

Lamhamed MS**,** Bernier PY**,** Hébert C. **1997**. Effect of shoot size on the gas exchange and growth of containerized Picea mariana seedlings under different watering regimes. *New Forests* **13**: 209–223.

Lamhamedi M**,** Lambany G**,** Margolis H**,** Renaud M**,** Veilleux L**,** Bernier PY. **2001**. Growth, physiology, and leachate losses in *picea glauca* seedlings (1+ 0) grown in air-slit containers under different irrigation regimes. *Canadian Journal of Forest Research* **31**: 1968–1980.

Landis TD. **2011**. The target plant concept. A history and brief overview. *National Proceedings: Forest and Conservation Nursery Associations-2010. Fort Collins, CO: USDA Forest Service, Rocky Mountain Research Station*: 61–66.

Landis TD**,** Dumroese RK. **2006**. Applying the target plant concept to nursery stock quality. Plant quality: a key to success in forest establishment. Proceedings of the National Council for Forest Research and Development (COFORD) conference, Dublin, Ireland.1–10.

Landis TD**,** Tinus RW**,** McDonald SE**,** Barnett JP. **1990**. Containers and growing media. Vol. 2 of The Container Tree Nursery Manual, Agricultural Handbook 674. *US Department of Agriculture, Forest Service, Washington, DC, USA*.

Lavender DP. **1984**. Plant physiology and nursery environment: interactions affecting seedling growth. Forestry nursery manual: Production of bareroot seedlings. Springer, 133–141.

Lawry D**,** Gardner J. **2001**. TREENET pilot study of street tree planting in South Australia.: 63.

Loh FCW**,** Grabosky JC**,** Bassuk NL. **2003**. Growth response of *Ficus benjamina* to limited soil volume and soil dilution in a skeletal soil container study. *Urban Forestry & Urban Greening* **2**: 53–62.

Luis VC**,** Puértolas J**,** Climent J**,** Peters J**,** González-Rodríguez ÁM**,** Morales D**,** Jiménez MS. **2009**. Nursery fertilization enhances survival and physiological status in Canary Island pine (*Pinus canariensis*) seedlings planted in a semiarid environment. *European Journal of Forest Research* **128**: 221–229.

Mariotti B**,** Maltoni A**,** Chiarabaglio PM**,** Giorcelli A**,** Jacobs DF**,** Tognetti R**,** Tani A. **2015**. Can the use of large, alternative nursery containers aid in field establishment of *Juglans regia* and *Quercus robur* seedlings? *New Forests* **46**: 773–794.

Marshall MD**,** Gilman EF. **1998**. Effects of nursery container type on root growth and landscape establishment of *Acer rubrum* L. *Journal of Environmental Horticulture* **16**: 55–59.

Marx DH**,** Barnett JP. **1974**. Mycorrhizae and containerized forest tree seedlings. North american containerized forest tree seedling symposium. Denver, Colorado,.

Mattsson A. **1997**. Predicting field performance using seedling quality assessment. *New Forests* **13**: 227–252.

McConnaughay KDM**,** Bazzaz FA. **1991**. Is physical space a soil resource? *Ecology* **72**: 94–103.

McDonald PM. **1991**. Container seedlings outperform barefoot stock: Survival and growth after 10 years. *New forests* **5**: 147–156.

Mexal JG**,** Landis TD. **1990**. Target seedling concepts: height and diameter. Target seedling symposium, meeting of the western forest nursery associations, general technical report RM-200.17–35.

Miller RW**,** Hauer RJ**,** Werner LP. **2015**. *Urban forestry: planning and managing urban greenspaces*. Long Grove, IL, USA: Waveland Press.

Mitchell RJ**,** Cox GS**,** Dixon RK**,** Garrett HE**,** Sander IL. **1984**. Inoculation of three *Quercus* species with eleven isolates of ectomycorrhizal fungi. II. Foliar nutrient content and isolate effectiveness. *Forest Science* **30**: 563–572.

Mollá S**,** Villar-Salvador P**,** García-Fayos P**,** Rubira JLP. **2006**. Physiological and transplanting performance of *Quercus ilex* L.(holm oak) seedlings grown in nurseries with different winter conditions. *Forest Ecology and Management* **237**: 218–226.

Moore D. **2001**. Nursery practices and the effectiveness of different containers on root development. Treenet proceedings of the 2nd National Street Tree Symposium.6–7.

Nelson W. **1996**. Container types and containerised stock for New Zealand afforestation. *New Zealand Journal of Forestry Science* **26**: 184–190.

NeSmith DS**,** Duval JR. **1998**. The effect of container size. *HortTechnology* **8**: 495–498.

Nowak DJ**,** Kuroda M**,** Crane DE. **2004**. Tree mortality rates and tree population projections in Baltimore, Maryland, USA. *Urban Forestry & Urban Greening* **2**: 139–147.

Omi SK**,** Howe GT**,** Duryea ML. **1986**. First-year field performance of Douglas-fir seedlings in relation to nursery characteristics. Proceedings of the combined western forest nursery council and intermountain nursery association meeting.12–15.

Ortega U**,** Majada J**,** Mena-Petite A**,** Sanchez-Zabala J**,** Rodriguez-Iturrizar N**,** Txarterina K**,** Azpitarte J**,** Duñabeitia M. **2006**. Field performance of *Pinus radiata* D. Don produced in nursery with different types of containers. *New Forests* **31**: 97–112.

Pandit R**,** Polyakov M**,** Tapsuwan S**,** Moran T. **2013**. The effect of street trees on property value in Perth, Western Australia. *Landscape and Urban Planning* **110**: 134–142.

Pardos M**,** Royo A**,** Gil L**,** Pardos JA. **2003**. Effect of nursery location and outplanting date on field performance of *Pinus halepensis* and *Quercus ilex* seedlings. *Forestry* **76**: 67–81.

Passioura JB. **2002**. Soil conditions and plant growth. *Plant, Cell {&} Environment* **25**: 311–318.

Peterson J. **1997**. Growing environment and container type influence field performance of black spruce container stock. *New Forests* **13**: 329–339.

Picard N**,** Saint-André L**,** Henry M. **2012**. *Manual for building tree volume and biomass allometric equations: From field measurement to prediction*. Rome/Montpellier: FAO/CIRAD.

Pinto JR. **2011**. Morphology targets: What do seedling morphological attributes tell us? *National Proceedings: Forest and Conservation Nursery Associations-2010. Fort Collins, CO: USDA Forest Service, Rocky Mountain Research Station*: 74–79.

Pinto JR**,** Dumroese RK**,** Davis AS**,** Landis TD. **2011a**. Conducting seedling stocktype trials: a new approach to an old question. *Journal of Forestry* **109**: 293–299.

Pinto JR**,** Marshall JD**,** Dumroese RK**,** Davis AS**,** Cobos DR. **2011b**. Establishment and growth of container seedlings for reforestation: A function of stocktype and edaphic conditions. *Forest Ecology and Management* **261**: 1876–1884.

Poorter H**,** Garnier E. **1999**. Ecological significance of inherent variation in relative growth rate and its components. In: Pugnaire F, In: Valladares F, eds. Handbook of functional plant ecology. New York, NY, USA: Marcel Dekker, 81–120.

Poorter H**,** Bühler J**,** Dusschoten D van**,** Climent J**,** Postma JA. **2012**. Pot size matters: a meta-analysis of the effects of rooting volume on plant growth. *Functional Plant Biology* **39**: 839–850.

Puttonen P. **1997**. Looking for the ‘silver bullet’–can one test do it all? *New Forests* **13**: 9–27.

Ran Y**,** Bar-Yosef B**,** Erez A. **1992**. Root volume influence on dry matter production and partitioning as related to nitrogen and water uptake rates by peach trees. *Journal of Plant Nutrition* **15**: 713–726.

Rietveld WJ. **1989**. Transplanting stress in bareroot conifer seedlings: its development and progression to establishment. *Northern Journal of Applied Forestry* **6**: 99–107.

Ritchie GA. **1984**. Assessing seedling quality. In: Duryea ML, In: Landis TD, eds. Forestry nursery manual: Production of bareroot seedlings. Corvallis, OR, USA: Springer, 243–259.

Rose R**,** Haase DL. **2005**. Root and shoot allometry of bareroot and container Douglas-fir seedlings. *New Forests* **30**: 215–233.

Rose R**,** Hasse L. **1995**. The target seedling concept: Implementing a program. *Forest and conservation nursery associations, USDA, Portland*: 124–130.

Rose R**,** Atkinson M**,** Gleason J**,** Sabin T. **1991**. Root volume as a grading criterion to improve field performance of Douglas-fir seedlings. *New Forests* **5**: 195–209.

Rose R**,** Carlson WC**,** Morgan P. **1990**. The target seedling concept. *Combined meeting of the western forest nursery association.*: 1–8.

Royo A**,** Gil L**,** Pardos JA. **2001**. Effect of water stress conditioning on morphology, physiology and field performance of *pinus halepensis* mill. seedlings. *New Forests* **21**: 127–140.

Schultz RC**,** Thompson JR**,** Others. **1990**. Nursery practices that improve hardwood seedling root morphology. *Tree Planters’ Notes* **41**: 21–32.

South DB**,** Mitchell RG. **2006**. A root-bound index for evaluating planting stock quality of container-grown pines. *Southern African Forestry Journal* **207**: 47–54.

South DB**,** Zwolinski JB. **1997**. Transplant stress index: a proposed method of quantifying planting check. *New Forests* **13**: 315–328.

South DB**,** Harris SW**,** Barnett JP**,** Hainds MJ**,** Gjerstad DH. **2005**. Effect of container type and seedling size on survival and early height growth of *Pinus palustris* seedlings in Alabama, USA. *Forest Ecology and Management* **204**: 385–398.

Standards Australia Limited. **2015**. *AS 2303:2015 Tree stock for landscape use*. Sydney, Australia.

Stape JL**,** Gonçalves JLM**,** Gonçalves AN. **2001**. Relationships between nursery practices and field performance for *Eucalyptus* plantations in Brazil. *New Forests* **22**: 19–41.

Stowe DC**,** Lamhamedi MS**,** Margolis HA. **2001**. Water relations, cuticular transpiration, and bud characteristics of air-slit containerized *picea glauca* seedlings in response to controlled irrigation regimes. *Canadian Journal of Forest Research* **31**: 2200–2212.

The British Standards Institution. **2014**. *Trees: from nursery to independence in the landscape - Recommendations*. London, United Kingdom.

Thompson BE. **1985**. Seedling morphological evaluation: what you can tell by looking. In: Durvea M, ed. Evaluating seedling quality: Principles, procedures, and predictive abilities of major tests. Corvallis, OR: Forest Research Laboratory. Oregon State University, 59–71.

Timmer V**,** Armstrong G. **1989**. Growth and nutrition of containerized *pinus resinosa* seedlings at varying moisture regimes. *New Forests* **3**: 171–180.

Tinus RW. **1974**. Characteristics of seedlings with high survival potential. Proceedings of the North American Containerized Forest Tree Seedling Symposium, Denver, Colorado.276–282.

Tran N. **2016**. Irrigation scheduling based on cumulative vapour pressure deficit to predict nursery tree water stress.

Trubat R**,** Cortina J**,** Vilagrosa A. **2008**. Short-term nitrogen deprivation increases field performance in nursery seedlings of Mediterranean woody species. *Journal of Arid Environments* **72**: 879–890.

Trubat R**,** Cortina J**,** Vilagrosa A. **2010**. Nursery fertilization affects seedling traits but not field performance in *Quercus suber* L. *Journal of Arid Environments* **74**: 491–497.

Trubat R**,** Cortina J**,** Vilagrosa A. **2011**. Nutrient deprivation improves field performance of woody seedlings in a degraded semi-arid shrubland. *Ecological Engineering* **37**: 1164–1173.

Tsakaldimi M**,** Zagas T**,** Tsitsoni T**,** Ganatsas P. **2005**. Root morphology, stem growth and field performance of seedlings of two Mediterranean evergreen oak species raised in different container types. *Plant and soil* **278**: 85–93.

Villar-Salvador P**,** Planelles R**,** Enríquez E**,** Rubira JP. **2004a**. Nursery cultivation regimes, plant functional attributes, and field performance relationships in the Mediterranean oak *Quercus ilex* L. *Forest Ecology and Management* **196**: 257–266.

Villar-Salvador P**,** Planelles R**,** Oliet J**,** Peñuelas-Rubira JL**,** Jacobs DF**,** González M. **2004b**. Drought tolerance and transplanting performance of holm oak (*quercus ilex*) seedlings after drought hardening in the nursery. *Tree Physiology* **24**: 1147–1155.

Wakeley PC. **1954**. *Planting the southern pines*. US Forest Servce, Department of Agriculture.

Wall A**,** Heiskanen J. **2003**. Effect of air-filled porosity and organic matter concentration of soil on growth of *picea abies* seedlings after transplanting. *Scandinavian Journal of Forest Research*: 344–350.

Ware GH. **1994**. Ecological bases for selecting urban trees. *Journal of Arboriculture* **20**: 98.

Watson WT. **2005**. Influence of tree size on transplant establishment and growth. *HortTechnology* **15**: 118–122.

Watson GW**,** Himelick EB. **1982**. Root distribution of nursery trees and its relationship to transplanting success. *Journal of Arboriculture* **8**: 225–229.

Watson GW**,** Sydnor TD. **1987**. The effect of root pruning on the root system of nursery trees. *Journal of Arboriculture (USA)*.

Watson GW**,** Himelick EB**,** Others. **1997**. *Principles and practice of planting trees and shrubs*. International Society of Arboriculture Champaigne, IL.

Westoby M**,** Falster DS**,** Moles AT**,** Vesk PA**,** Wright IJ. **2002**. Plant ecological strategies: some leading dimensions of variation between species. *Annual review of ecology and systematics*: 125–159.

Wightman KE. **1999**. *Good tree nursery practices: practical guidelines for community nurseries* (B Hince, Ed.). International Centre for Research in Agroforestry.

Wilcox HE. **1968**. Morphological studies of the roots of red pine, *Pinus resinosa*. II. Fungal colonization of roots and the development of mycorrhizae. *American Journal of Botany*: 688–700.

Will RE**,** Teskey RO. **1997**. Effect of elevated carbon dioxide concentration and root restriction on net photosynthesis, water relations and foliar carbohydrate status of loblolly pine seedlings. *Tree Physiology* **17**: 655–661.

Wilson BC**,** Jacobs DF. **2006**. Quality assessment of temperate zone deciduous hardwood seedlings. *New Forests* **31**: 417–433.

Wilson ER**,** Vitols KC**,** Park A. **2007**. Root characteristics and growth potential of container and bare-root seedlings of red oak (*Quercus rubra* L.) in Ontario, Canada. *New Forests* **34**: 163–176.

Wrzesiński P. **2015**. The influence of seedling density in containers on morphological characteristics of European beech. *Forest Research Papers* **76**: 304–310.

Zianis D**,** Muukkonen P**,** Mäkipää R**,** Mencuccini M. **2005**. Biomass and stem volume equations for tree species in Europe. *Silva Fennica Monographs* **4**: 63.

Zida D**,** Tigabu M**,** Sawadogo L**,** Odén PC. **2008**. Initial seedling morphological characteristics and field performance of two Sudanian savanna species in relation to nursery production period and watering regimes. *Forest Ecology and Management* **255**: 2151–2162.