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 forestry 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 of trees 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 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 urban heat islands threaten the survivability of urban trees, and success of green infrastructure (HIA, 2016). Additionally, tree selection 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 may be wasted if the quality of the planted seedling is initially poor (Moore, 2001). Confounded 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 too infrequently or only when problems arise (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). Multiple tests of nursery stock attributes are necessary because there is no single characteristic which encompasses tree quality, which is analogous to a physician conducting several measurements to characterize a patient’s 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 the likelihood of survival (Grossnickle, 2012). As tree stock are initially acclimatized to nursery conditions and not necessarily 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 rapid growth phase in production (Mattsson, 1997). Regardless, the ultimate goal of a generating a high quality tree stock is to ensure a very high percentage of successful 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 inexpensive and quick physiological tests are lacking at present, 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, whereas 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 useful measureable traits 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, such as aboveground sturdiness or the physiological balance between shoots and roots(Wightman, 1999). Importantly, no single morphological factor has been shown to provide a perfect prediction of out-planting success, but height, stem diameter, root volume and root:shoot are all 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), including national and international standards for growing nursery stock (see Canadian Nursery Landscape Association, 2006; European Nurserystock Association, 2010; AmericanHort, 2014; Standards Australia Limited, 2015). 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 influence tree stock growth and 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 for a given container volume or rootball diameter, 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 for a given root system size 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. Large size class nursery trees are also difficult to lift, handle and plant properly, which can negate advantages of larger nursery tree stock in planting success (Cleary *et al.*, 1978).

Tree stock diameter is traditionally viewed as an index for sturdiness for nursery tree stock. Stem diameter at the base of the tree increases concomitantly with total tree height, but in tree nurseries this relationship is affected by growing density, fertility and pruning practices (Mexal & Landis, 1990). Positive relationships with stem 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 container tree stock produced for forestry plantations in the USA 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 that improves 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, the physical volume of roots 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). However, the physical volume of the roots in a given container size could reflect either a fibrous root system or a root system with large tap roots (Haase & Others, 2007). Given the importance of an intact and supportive rootball at planting, 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). Thus, assessments of root system quality may be affected by variation in root morphology across species or 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 through restriction the water transport 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 in tree stock 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 *Pinus palustris* and *Pinus elliottii* 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). 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). Adaptation of this concept has led to a suite of quality assessment criteria that are now essential elements in nursery stock quality testing protocols worldwide. 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 two 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 plant taper and reflects an ability to withstand mechanical damage via bending, etc. (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, it was not related to field performance in silver birch (Aphalo & Rikala, 2003). This discrepancy 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 should not be too tall relative to the stem diameter and the shoot mass not too large relative to the initial root ball size (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 related stress (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 leaf surface area 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 tree stock possess complete root systems oriented downward (McDonald, 1991). Bareroot tree stock 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), and likely decreased root desiccation from exposure which is observed in bare root stock (Girard *et al.*, 1997). 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 sized shoots 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, notably with preferential loss of fine roots, while containerized seedlings typically maintain an 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 of root mass to shoot mass), with harvested bareroot trees generally having a root:shoot of 1:3 compared to containerized tree with a root:shoot of 1:2 (Schultz *et al.*, 1990; Haase & Others, 2007). Deciduous bare root trees, however, are often planted into containers to produce larger size trees that can also be planted year round. 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 oriented 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 into root, shoots or leaves(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 under stress 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, container spacing, 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 larger container tree with a higher rate of survival that a less expensive smaller container 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 sized 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 far smaller than containers now used for nursery trees for landscape use (>1000 L). Increases, decrease and no effect of container volume on root:shoot biomass 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 < 20 L. 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 for 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). Alternatively, toxicity and reduced growth can result from over-fertilization of nitrogen and phosphorus in Australian sclerophyll tree species that are naturally associated with low fertility soil (Groves & Keraitis, 1976).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 nutritional hardening by reduction nitrogen supply 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 eucalypt 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 three 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 slow-growing trees often originate from nutrient-poor environments such as 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.

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