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

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# 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 composing 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). In 2015, the Australian nursery industry adopted a new standard (**AS2303**) to assess the quality of tree stock for landscape use (Standards Australia Limited, 2015). This new standard was designed to assess above- and belowground characteristics of production tree stock for all stages of growth. Although the **AS2303** standard is not currently mandatory, it is likely to be increasingly called upon in order to minimize risks of out-planting failure with new landscape and green infrastructure projects.

## Assessing Seedling Quality

Evaluating nursery seedling quality is necessary to understanding seedling development and the capacity for growth after out-planting (Wakeley, 1954), yet the quality of tree stock is often assessed inconsistently (Haase, 2008). Nursery seedlings should embody the structural and physiological traits that can be quantitatively linked to success in the field (Rose *et al.*, 1990). Seedling quality is a dynamic process that is the culmination of all the practices that have preceded the assessment (Mexal & Landis, 1990). The term "stock type" is used to describe a seedlings age and method production, while also serving as a visual reference of what the seedling should look like before out-planting (Pinto *et al.*, 2011a). A primary goal of seedling quality assessments is to quantify attributes which accurately assess the condition and potential for growth of different stock types (Wilson & Jacobs, 2006). As there is no single test which encompasses seedling quality, assessing a seedling is analogous to a physician conducting a multitude of measurements to characterize a patients general health (Ritchie, 1984).

Seedling 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, planting seedlings with desirable plant attributes will not guarantee survival, but should increase survivability (Grossnickle, 2012). As seedlings 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 seedling 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. Thus, specifications for tree stock are designed to ensure that seedlings can endure stresses from variable site conditions and growing climates, but are also applicable to a wide range to species and tree types.

## Grading seedling morphology

Nursery 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 tree stock can change significantly between production and out-planting, while seedling morphology tends to stay the same (Pinto, 2011). As a result, non-destructive measurements of seedling form and structure are commonly used as indices of quality and as surrogates for physiology.

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 response to 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 seedling quality as they retain their mark on the seedling identity for extended time frames after seedlings are field planted and start to grow (Puttonen, 1997; Grossnickle, 2012).

The main morphological attributes used to grade 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 seedling 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 seedling performance potential (Mattsson, 1997; Haase & Others, 2007). Of these, height and diameter are easily the two most common parameters examined in tree stock, and minimum and maximum targets are usually established in grower specifications (Thompson, 1985; Haase, 2008). Assessments used to describe a quality nursery plant generally convert these core morphological characteristics into grading standards (Landis & Dumroese, 2006).

### Aboveground

Metrics of shoot system size relate how available soil water and nutrients, competition for light limited seedling 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 seedling should be as tall as possible while still possessing an acceptable level of survival potential for the designated site (Thompson, 1985). Larger seedling height, however, can have adverse effects on field success in drier sites. This is because taller seedlings 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. Additionally, larger stock adds difficulty in lifting, handling and planting properly, which can negate advantages of larger size 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 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 seedling 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 seedlings quality (Wrzesiński, 2015), yet these parameters remain difficult to monitor during nursery production. Recently planted seedlings 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 of seedlings to take up water so they can initiate the establishment process (Carlson & Miller, 1990; Wrzesiński, 2015), and establishment is dependent on the capacity of seedlings to rapidly initiate new roots (Heiskanen & Rikala, 1998, Grossnickle (2005)). In turn, 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 height of tree stock 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 seedlings 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). Importantly, assessing the quality of root development will be affected by inherent variation across species, as well as 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 the large increase in containerized seedlings is that seedlings 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 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 seedlings (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. Additionally, measurements of root system morphology can be destructive and time consuming, which limits their application in nursery cultural practices (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 seedlings 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 likely represent the most cost-effective standard practice.

### Building quantitaive links between morphological parameters

The realization that no single factor predicts seedling success led to the 'target seedling concept' by Rose *et al.* (1990), which proposes that numerous physiological and morphological seedling traits should be tracked and developed to quantitatively assess seedling performance (Rose & Hasse, 1995). An overarching aim of the target seedling approach is that seedling quality is of the utmost importance. Global adaptation of this concept has led to a suite of quality assessment criteria that are now essential elements in seedling testing standards. It is now 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 therefore been adopted to better assess overall seedling 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 seedling quality than with single parameters (Jacobs *et al.*, 2005). Consequently, morphological indexes combining multiple morphological measurements better correlate to beneficial seedlings attributes and seedling 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 likely insufficient to capture the overall balance of nursery 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). Consequently, 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 tree stock at higher risk of transplant shock (Rietveld, 1989; South & Zwolinski, 1997), which is important for tree stock grown for landscape use.

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). Too high a shoot mass can decrease survival as evaporative surface exceeds water uptake capacity, while too low a 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 quality and predict future health.

## Impact of nursery practices on tree stock balance

Nursery silvicultural practices have a strong influence on seedling performance immediately after planting (Grossnickle, 2012). Thus, morphological parameters used to assess tree stock are likely to exhibit a high degree of variation across different production nurseries. For example, improper nursery management may encourage a disproportionate amount of shoot growth, resulting in an unbalanced seedling with lower field-survival potential (Cleary *et al.*, 1978). Below we review aspects of nursery practices, common in Australia, that feedback to overall root:shoot balance of tree stock.

### 1. Use of bareroot vs. container tree stock

**i think bareroot in the literature is in grown trees that are dug out and directly planted** **this is a different terminology than bare root trees in australia** Tree stock quality assessments show bare-root seedlings have larger shoot systems because they are typically grown at lower densities, and in many instances longer time-frames, than container seedlings (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 (Tinus, 1974; Rose & Haase, 2005). Consequently, quality bareroot seedlings generally have root:shoot ratio of 1:3 or less and quality container seedlings have root:shoot ratio 1:2 or less (Haase & Others, 2007). The removal procedure for bare-root trees produces an imbalance in the root:shoot ratio and reduces the chance for successful field establishment and competitive growth of seedlings (Schultz *et al.*, 1990). Fundamental differences between these two stock types are important for nursery decision making in the context of the ‘target seedling’ concept, as optimal seedling size conclusions still apply to both (Aphalo & Rikala, 2003).

Container seedlings have the advantage of possessing complete root systems oriented downward, with at least one in a position to become a taproot (McDonald, 1991). Plants grown in containers, however, generally have a different root morphology than field-grown plants (NeSmith & Duval, 1998). Regardless, containerized seedlings still tend to have greater initial root growth during the following out-planting than bare-root seedlings (Johnson *et al.*, 1984; Wilson *et al.*, 2007). Container-grown trees are considered to better meet the transpirational needs of the plant immediately after transplanting compared to bare-root stock (Harris & Gilman, 1993), however, these less disturbed root systems do not always increase shoot growth in subsequent years following out-planting (Rose & Haase, 2005).

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). Overall, containerized seedlings are easier to plant, have more immediate growth response benefits, and are cheaper to produce than bare-root seedlings (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 nursery standards are now regulating the size of the bare-root seedling rootball removed in relation to the size of the tree aboveground (AmericanHort, 2014; The British Standards Institution, 2014). Consequently, it is an essential need to develop reliable quality assessment protocols that distinguish between these two stock types.

### 2. Container type

The container design used for tree stocktypes has a major influence on root systems (Landis *et al.*, 1990, Chapman & Colombo (2006)), and thus overall tree balance. 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 nursery containers (Gilman *et al.*, 2010).

Containers that auto-prune roots may inadvertently alter natural patterns of tree biomass investment (Climent *et al.*, 2008), thus 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 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 then 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 feed-backs to physiology, growth and tree balance, and should be prioritized to improve overall seedling 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 above- and belowground, which manifest in multiple ways. 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). This 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 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 tree nurseries that produce a large variety of species for landscape use.

The increasing demand for larger size trees for urban landscape plantings 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 now commonly used for nursery trees for landscape use (up to 2500 L). 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 species grown for landscape use are 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 (e.g nitrogen) 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 and decreased carbohydrate production, tree slenderness, height and caliper (Trubat *et al.*, 2010). Overall, above- and belowground 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).

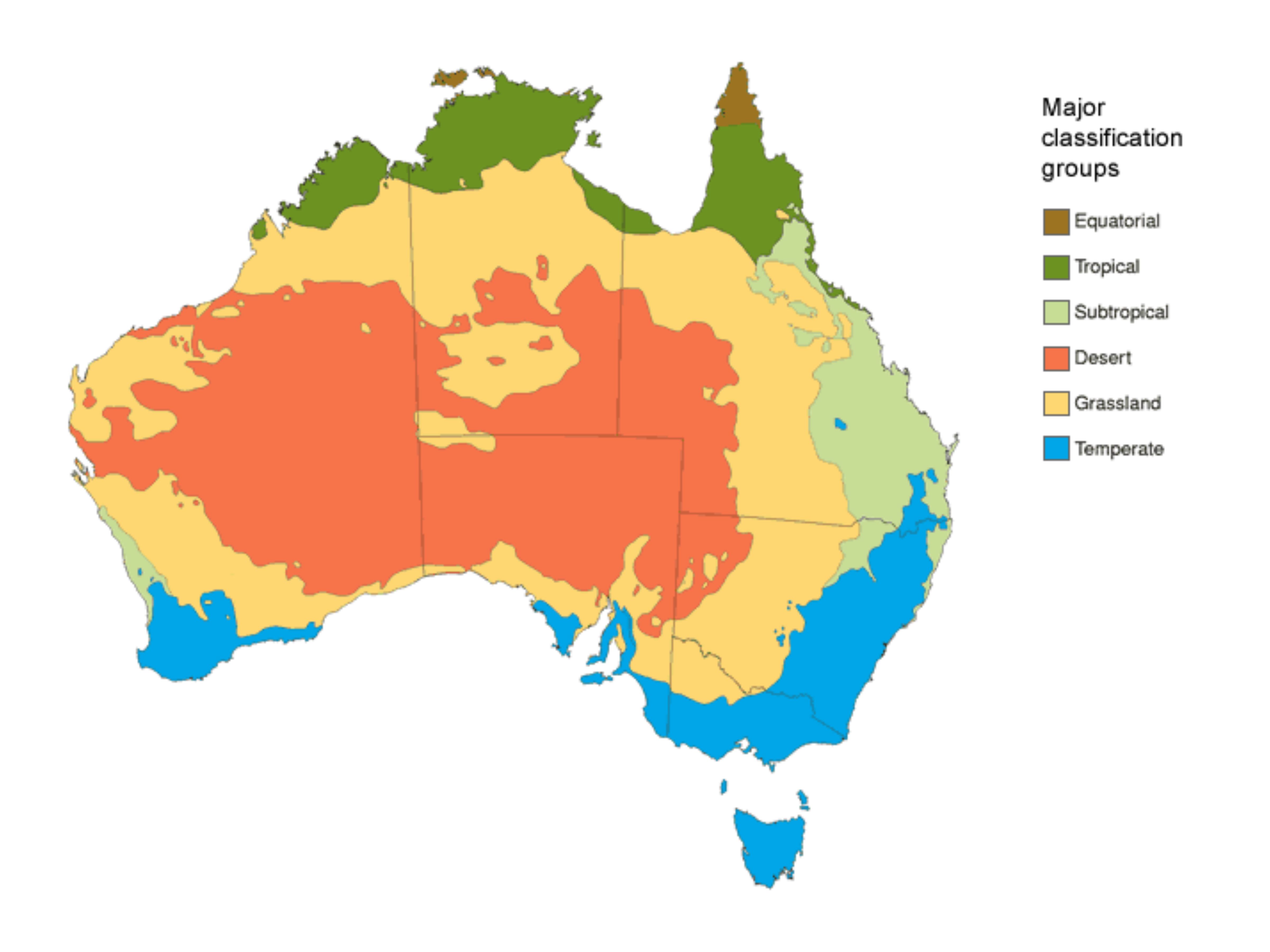
Growing media (potting soil) must be porous enough to provide efficient exchange of oxygen and carbon dioxide, while also having a sufficient water holding capacity to supply water to the plant (Landis *et al.*, 1990; Heiskanen, 1993). The use of different growing media, to control soil structure, nutrition, 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 (Wall & Heiskanen, 2003). Management strategies for trees for landscape use 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 root and shoots.

# Impact of climate on nursery tree stock

Different environmental conditions can have important influences on functional traits of common seedling types (Mollá *et al.*, 2006), which is of specific importance when designing nursery quality criteria for broad geographic regions. Consequently, tree quality 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). In Australia, the geographic location of a nursery may play a key role in differences between growth and balance of similar stock types.

Existing research on the impacts of climate on nursery stock focuses heavily on growing season cycles of deciduous tree stock or with 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 variety of native broad-leaf evergreen tree stock grown in Australian nurseries. Thus, 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 (<http://www.bom.gov.au>, Figure 1). Most production nurseries in Australia grow containerized trees in open environments. As seedling 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 seedlings are found with changes in temperature and the intensity, quality, and duration of light (Callaham, 1962). This raises the question of whether differing growing climates affect seedling morphological parameters related to tree balance and then how large of an impact does climate variability have on growth of Australian nursery tree stock?

 Figure 1. Major climate regions of Australia.

## 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. Trees most also endure varying degrees of these stresses from the enviroment when out-planted, 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), which increases the potential for transplant shock in tree stock grown for landscape use.

Out-planting success depends on the interactions between tree attributes and the environmental components 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).

# Assessing root:shoot balance in Australian tree nurseries for landscape use

The issue of a lack of standardized method for determining root:shoot balance in nursery plants raised by Lavender (1984) still exists today. 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), and thus is commonly used to estimate the size of the aboveground portion of an individual tree. 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 provides a simple characterization of root system morphology (Jacobs *et al.*, 2005), but actual measurements of root volume may not be practical or cost effective for landscape-based nurseries producing large size trees.

In **AS2303**, a simplified aboveground volume based parameter ('Size Index') is generated from the product of stem caliper at 300 mm and total height (Standards Australia Limited, 2015). This parameter, generalized for all species, is then related to the size of the container at dispatch. The assessment criteria stipulates that root occupancy inside of the container must be high, thus allowing container volume to provide an reasonable indice of root system size. Minimum and maximum acceptable values of 'Size Index' are then specified for the extremely large range of container volumes used in Australian landscape-based tree nurseries. This grading criteria provides a new method to assess the overall balance of a nursery tree, different from other international nursery standards. These other standards stipulate appropriate ranges of height, caliper, canopy spread or tree slenderness for different container sizes or rootball dimensions (Canadian Nusery Landscape Association, 2006; European Nurserystock Association, 2010; AmericanHort, 2014; The British Standards Institution, 2014). However, most of these existing standards do not include tree balance specifications for large container sizes that are frequently utilized for growing landscape trees.

# Evaluating the Australian standard for nursery tree stock

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. The question still remains over whether specified ranges of morphological parameters or indexes used to assess the quality of tree stock accurately encompass inherent variation that exists within and among species. Large differences in growth rates exists across species or plant types, which plays a critical role in how different trees 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). Whether the specified correlation between aboveground 'Size Index' and rooting volume in **AS2303** captures this variation in tree growth for the large range of deciduous, evergreen, native and non-native landscape trees produced in Australian nurseries has yet to be explicitly studied.

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). Given this variation in plant form, generalized allometric equations to predict aboveground tree size may not be suitable for all species without significant error (Hunter *et al.*, 2013). As a result, the ability of the 'Size Index' parameter to be used as a general tool to correlate aboveground size to rooting volume needs to be tested empirically. Additionally, prevailing climate and different irrigation and fertilization regimes across nursery sites affect seedling quality during production (Mattsson, 1997). 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 nursery practices and the wide variability in regional climate in Australia affect the current quality assessment criteria in **AS2303** is unknown and requires further evaluation.

# Future Directions

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 even species origin (native/non-native). As information is gained with local nurseries, specifications for containerized plants are likely to change to more accurately match site, species, and planting time to individual stock type (Nelson, 1996). If superior morphological predictors can be identified it may be possible to modify nursery cultural techniques to improve quality (Wilson & Jacobs, 2006).

**AS2303** uniquely delineates a 'Size Index' range for a tree shoot system in proportion to a continuum of containers sizes starting at 20 L. This is a unique attempt to quantify and standardize above and belowground balance in landscape-based nursery tree stock produced in Australia. Proper balance between root and shoot systems is critical to increase the potential for survival of out-planted trees to landscape environments, and likely should be evaluated in quality assessments of larger nursery trees. If use of 'Size Index' and its relationship with rooting volume provides an accurate assessment of tree stock balance, it provides a tool for both Australian growers and buyers of landscape trees to use to better meet the increasing green space demands outlined in the "202020 Vision".

If measured variation in tree stock from species differences, climate or nursery practices suggest this new index inadequately describes overall tree stock balance, however, its usage may inhibit the long-term goals of the "202020 Vision". Many existing nursery tree standards (non-Australian) include quality specifications for different classifications of tree stock (i.e. spreading, upright, evergreen, deciduous, etc.), while **AS2303** provides one single guideline for all tree stock. If empirical evaluations suggest the specified 'Size Index' approach should be amended, then further categorization of Australian tree stock represents a potential avenue to improve tree balance assessment criteria. In should also be explicitly mentioned that robust survival and field establishment experimental trials should be undertaken to ensure that current and future iterations of tree balance criteria positively correlate to out-planting success.

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