Root to shoot balance in Australia tree stock

COURTNEY E. CAMPANY1, and MARK TJOELKER1

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

Hawkesbury Institute for the Environment, Western Sydney University Hawkesbury Campus Ground Floor, Building R2 Locked Bag 1797 Penrith 2751 NSW Australia

Corresponding author: CE Campany, email: [courtneycampany@gmail.com](mailto:courtneycampany@gmail.com), telephone: +61 02 4570 1421, fax: +61 02 4570 1103

# Trends in australia 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 the plantation estate (>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 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 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 tree nurseries to provide tree stock that can endure increasing 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.

In 2015, the Australian nursery industry adopted a new standard for tree stock for landscape use to assessment above and belowground characteristics of tree stock of all stages of growth (AS2303:2015). Confounding with the demands for diverse high quality tree stock on the nursery industry is that variability within tree stock is a near certainty during nursery production. This variability presents a unique challenge for nurseries attempting to produce planting stocks with uniform morphological characteristics (Puttonen, 1997), and thus meeting specifications outlined in the AS2303 standard. Although the AS2303 standard is not currently mandatory, it is likely to be increasingly called on in attempts to minimize risks of out-planting failure with new landscape and green infrastructure projects. Selecting the appropriate cultivar, properly preparing the out-planting site and management of out-planted trees will be wasted of the equality of the out-planted seedling is initially poor (Moore, 2001). 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.

## Assessing Seedling Quality

Evaluating nursery seedling quality is thus necessary to understanding seedling development and the capacity for growth after out-planting (Wakeley, 1954), however the quality of tree stock often is assessed inconsistently (Haase, 2008). Overall, 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 a culmination of all the practices that have preceded and will succeed that point for measurement (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 levels of morphological and physiological attributes which accurately assess the condition and potential for growth and development of different stock types (Wilson & Jacobs, 2006). As there is no one 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, assessments of stock type performance potential does 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.

## Primary stresses affecting nursery seedlings

The three primary types of stress that influence seedling quality are moisture, temperature, and physical stress.(Haase & Others, 2007). Nursery seedlings can be profoundly impacted by each of these stresses during nursery production, including culturing, lifting, packing, grading, handling, pruning, storage, and transport. Additionally, seedlings will undergo varying degrees of environmental stresses not experienced during nursery production. The varying degrees of harshness inherit by out-planted seedlings determine the length and severity of seedling 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 seedlings to the new environmental conditions (Close *et al.*, 2005). To overcome transplant stress after planting the root system must meet the transpiration demands of the shoot system (Ford, 2014). Reductions in stress should thus be actively managed with nursery practices that manage proper balance of tree planting stock above and belowground.

Minimizing transplant shock is highly relevant for tree stock in Australia as planned increases in urban green spaces are underway as well as climate and soil constraints that typically define Australian ecosystems. During an initial growth lag phase, reductions in water and nutrient uptake and the loss of root carbohydrates to regrowth roots will determine the amount of transplant shock and eventually out-planting success. 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). **one climate example** **one wrap up sentence about quality standards**

## target seedling approach (variables that are most related to growth---which morph variables are most correlated to those)

Nursery stock can be described by both morphological and physiological characteristics, but these characteristics must be related to out-planting performance (Landis & Others, 2011). Physiology and vigor can change significantly between harvest and out-planting while morphology tends not to change during that time, however, seedling morphology can serve as a proxy for physiology (Pinto & Others, 2011). Due to a lack of a rapid and encompassing physiological tests (Pinto *et al.*, 2011a), morphological and physiological assessments are rarely conducted in combination (find more Hobbs, 1984). Thus, tree nurseries commonly asses tree stock by focusing on characteristics of seedlings morphology, including non-destructive measurements of form and structure, as indices of quality and as surrogates for physiology.

Measuring morphology in the nursery is standard practice because it easily tracks growth and describes seedlings at harvest, and has thus evolved into classification which correlates seedling survival and growth with specific morphological traits (Pinto & Others, 2011, Ritchie 1984). The morphological attributes of seedlings represent the cumulative series of physiological processes responding to resources and stresses during nursery production (Mexal & Landis, 1990). 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)). 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).

The main morphological attributes used to address stock quality are: sturdiness, height, diameter, leaf area, health and root morphology (**needs updating** Simoes 1987; Guerreiro and Colli 1984). Consequently, seedlings quality represents how height, diameter, plant nutrition, health, root size and shape act together and influence one another (Wightman, 1999). Consequently, seedling morphological characteristics are best described with a combination of height, diameter, and root:shoot ratio (Cleary *et al.*, 1978). 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). No single morphological factor has been shown to provide a perfect prediction of out-planting success, but many of them are linked with seedling performance potential in some way (Mattsson, 1997; Haase & Others, 2007).

This realization that no one 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 field performance (Rose & Hasse, 1995). An overarching aim of the target seedling approach is that seedling quality is of the utmost importance, and global adaptation of this concept has led to a suite of quality assessment criteria, that are now essential elements in seedling testing standards. As a result, it is now commonly accepted that height and diameter measurements alone do not always correlate with seedling performance following out-planting. Ratios of various morphological traits (e.g., root:shoot, height:diameter) have therefore been adopted morphological studies to better assess overall seedling quality (Bayley and Kietzka 1997; Jacobs et al. 2006).For example, including height, stem diameter and shoot-root ratio each influence seedling tolerance to environmental stress and thus should be considered in relation to each other (Cleary *et al.*, 1978).

# mini-Review of common morphological indices

## Aboveground (Height, Diameter/Calliper)

Commonly-measured morphological characteristics include shoot height, stem diameter, and root system size (Rose *et al.*, 1990). Tree nursery standards from various countries generally focus on these 3 core parameters to assess tree stock balance, albeit in different ways. The first attempts to describe an quality nursery plant usually begin with morphological characteristics, such as shoot height and stem diameter, which are then converted into grading standards (Landis & Dumroese, 2006).

Shoot system size is important because on sites with available soil water and nutrients, competition for light between planted seedlings and the site vegetation complex is a main factor limiting seedling performance (Grossnickle 2000).

root system size:

*height* Height is considered a good estimate of photosynthetic capacity and transpirational area, suggesting a positive relationship with subsequent growth (Haase & Others, 2007). Within a nursery environment maximum shoot growth occurs at high soil water regimes and moderate to high fertility levels (Mexal & Landis, 1990). In regards to height, 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, may have adverse effects on field success in drier sites. This is due to the fact that taller seedlings incur greater water loss by transpiration and tend to use more water, despite haveing greater leaf surface area for photosynythesis (Carlson & Miller, 1990) This has led to nursery stock height being an inconsistent predictor of out-planting survival. Tree stock can this be culled for being too tall or too short, and thus with a poor R:S balance. 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).

*diameter* Tree stock diameter (caliper) is traditionally viewed as a index for sturdiness for nursery tree stock [all cites]. 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 noted for nursery tree stock species seedlings (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 operationally attractive morphological 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 a variety of nursery grown tree seedlings (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 tree seedling container stock has been increasing, however evidence that subsequent increases in seedling diameter led to increased field performance is lacking (South *et al.*, 2005).

Stem diameter at the time of planting can also predict of stem volume for several years after out-planting (Simpson 1995).

### Belowground (Rootball diameter and volume)

Root system parameters are some of the best features to characterize seedlings quality (Wrzesiński, 2015), yet these parameters remain difficult to monitor in production tree nurseries. Recently planted seedlings will initially depend on the root system created by nursery culture (Grossnickle, 2005), thus anticipating the potential for seedling root proliferation following transplanting could greatly improve field establishment (Davis & Jacobs, 2005). New root growth will be paramount for seedlings access water and nutrient resources following out-planting. Seedling establishment is dependent on the capacity of seedlings to rapidly initiate new roots (Heiskanen & Rikala, 1998, Grossnickle (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). 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 nusery tree stock, root volume is shown to be postively 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 is importatnt for the root system to fully colonize the container and contain actively growing white roots tips. Seedlings with large numbers of lateral roots (representing active root tips) have more sites for mycorrhizal development and thus increased nutrient uptake and growth in the nursery [*recent* Wilcox (1968); Marx & Barnett (1974); Mitchell *et al.* (1984);].

*Importantly, lateral root morphology are not consistent across seedlings when predicting growth (davis cites), not enough cites and species.*

As new root must regenerate from the original out-planted root system, it is vital to also assess root distribution patterns of nursery tree stock(Watson & Himelick, 1982). If early stage root systems are disturbed in container or nursery manipulation, the root growth form can be permanently altered, sometimes with detrimental effects (Thompson, 1985). A potential issue with the large increase in containerized seedlings is that seedlings are subject to root-binding and spiraling, which can negatively affect out-planting performance for years (Cleary *et al.*, 1978). If left too long, root systems become bound with disproportiante 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 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). 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). Root spiraling was found occur in all *Pinus pinea* seedlings grown in containers, however, spiraling had no affect on success following out-planting (Dominguez-Lerena *et al.*, 2006).

## Pitfalls with morphological assessments and single parameter relationships

Issues with using only morphological assessments, especially involving single parameter estimates of quality, have long been recognized has having overly large variation. Use of simple morphological variables to predict absolute growth often fail to explain large proportions of variation out-planted seedling growth (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 longleaf 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. This issue represents a fundamental problem for the nursery industry, yet morphological indices still likely represent the most cost-effective standard practice.

# Building quantitaive links between morphological parameters above and bewlow ground

Insufficient grading rules of morphological parameters, may not capture natural variation in tree stock, and may lead to culling of stock that 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). Morphological indexes, including combinations of two or more morphological measurements, are used to describe an overall beneficial seedling attribute that corresponds to field performance better than any individual parameter (Thompson, 1985). Morphological indexes generally separate into 2 categories. First, are indices that combine morphological parameters to describe aspects of the aboveground architecture of plant. Second, are combinations of parameters above- and belowground which offer some assessment of overall seedling balance.

Tree slenderness index, calulated as the height:diameter ratio, 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 droughty planting conditions (Haase & Others, 2007; Ford, 2014). The slenderness index was correlated with mortality in **Pinus patula** seedlings, 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 arise from focusing only on aboveground grading criteria, which ignores the importance of root system morphology in growth and field survival and may not adequately identify potential for out-planting success (Schultz *et al.*, 1990).

Thus the question arises of whether grading aboveground metrics of seedlings size alone are sufficient to capture the state of the entire seedling. However, combining above and belowground indices of seedling quality will more reliably predict seedling field performance.

Typically considered as R:S but this parameter is not cheaply measured in production nurseries. As RCD has been shown to correlate with the size of the roots system it seems relevant to include morphological indexes which contain RCD with container size (is RCD vs container diameter or volume as in South & Mitchell (2006))

*morphological indexes* R:S = water uptake to loss relative canopy to root-ball volume

*1. Tree stock balance: relationship between 'Size Index' and Rootball Volume*  
2. Size Index (as Height x Caliper) (caliper or root collar diameter) \*4. Rootball (volume) (RGP)

## Review of Root : Shoot balance (need strong section here in terms of ecology and nurser specifics)

Combinations of root and shoot morphological characteristics may be better able to predict growth potentials and possibly out-planting success than simple shoot parameters. The challenge facing nursery growers producing trees is to not only optimize canopy growth but to ensure that the root and shoot systems are properly managed, especially with container production systems which affects the quality of the root systems (Moore, 2001).Transplant success and establishment is dependent on the chain of events from propagation and production, to harvest and transport, to transplanting and aftercare (Struve & Others, 2009). To be established, a transplanted tree must generate a root system so that shoot growth is comparable to a non-transplanted tree (Watson *et al.*, 1997). Establishment likely different for different stock types, such as large vs small caliper trees. The ability to re-establish a balance between above and belowground growth will depend on the rate of root growth potential, even with shoot growth being typically suppressed initially (Struve & Others, 2009). Larger trees generally require a longer time to produce a root system compared to smaller trees (Watson, 2005), which may affect out-planting success. An imbalance above and belowground can put larger tree stock at higher risk of transplant shock, thus eliminating the increased survivability usually seen over smaller seedlings (south and Mitchell 1999).

Proper R:S balance is an important morphological attribute because it is a measure of seedling water loss and water uptake capacity at the time of planting (Ritchie 1984; Thompson 1985; Burdett 1990; Grossnickle 2000), although this does not always translate into reduced water stress post-planting (Lamhamed *et al.*, 1997). The shoot-root ratio represents the balance between the transpirational area (shoot) and the water absorbing area (root) of a seedling (Thompson, 1985). Higher root:shoot ratio may result in more favorable water relations,lower shoot maintenance requirements and thus faster growth rates (Close *et al.*, 2010). Above the optimum shoot:root ratio, survival decreases with increased allocation to shoots as evaporative surface exceeds water uptake capacity, while below optimal shoot:root ratios, decreases drought survival due to a lack of photosynthetic capacity to produce needed carbohydrate reserves (Cregg, 1994). This is mainly a issue of an imbalanced root:shoot ratio, which affects water uptake and the ability to develop new roots (cites from gross2012, Haase & Others, 2007), ].  
From a structural point of view, the shoot and root system should also be balanced to ensure the stability of the seedling in the years following out-planting. To avoid toppling, the shoot system need not be to tall relative to the root system. Additionally, the root system should be of sufficient size to anchor the tree and the caliper of the shoot system should be developed enough to provide stability against mechanical forcing. In nursery trees, it is important that the shoot not be too tall relative to the stem diameter and that the shoot mass not be too large relative to the roots (Haase, 2008). A vigorous fast-growing shoot has to be supported and balanced by a vigorous root system (Nielsen 1992).

Shoot-root ratios can be confounded in quality assessment when a low value does not reflects a thick taproot system instead of a large fibrous roots= system, which offers limited surface area necessary for water absorption (Ambebe *et al.*, 2013). This highlights the need to combine R:S assessments with other aspects of seedlings morphology. Improved root:shoot ratios have been shown to be positively correlated with height growth in for seedlings [Larsen1998, others?]. Overall, a nursery may also choose to manage root:shoot balance differently when tree stock are destined to be out-planted in either arid or well irrigated environments.

*nurseries, how to achieve root:shoot assessment without destroying plants???* The issue of a lack of standardized method for determining root:shoot ratios in nursery plants raised by Lavender (1984) still exists today.In is difficult to determine a quantity of roots that should exist for individual tree stock, thus, R:S are used to when evaluating overall plant size and predicting field survival (Thompson, 1985). However, volume based methods are still destructive and not necessarily cost effective for production nurseries (SI has mass to root size). Under managed nurseries environments, catered to support tree stock growth, it will be difficult to develop an adequate index of root:shoot balance that will cover the saleable period for any given stock type. From an economic standpoint, nurseries must minimize the amount of seedlings that they destructively harvest when evaluating root shoot balance. Thus, non-destructive morphological parameters are commonly used to assess tree stock balance. How effective these are is still a matter of contention

# bareroot vs container stocktypes

The root–soil contact is more disrupted in bare-root seedlings through the loss of fine roots at lifting (Nambiar 1980; Struve and Joly 1992)Rose & Haase (2005), while containered seedlings typically maintain intact multidimensional root system (Tinus, 1974). Containered seedlings then to have greater initial root growth during the following out-planting (Johnson *et al.*, 1984; Wilson *et al.*, 2007)*more(cites in gross2012)*. Although root grown seems to be enhanced, this has not always been shown to increase shoot growth and survivability in subsequent years following out-planting(Rose & Haase, 2005). Overall, however, container production systems include better environmental control of the growing regime, shorter production cycles, increased stock uniformity and frequently superior field performance on poor quality sites (Brisette et al. 1991; Johnson et al. 1996). Container-grown trees have been shown to better meet the transpirational needs of the plant immediately after transplanting compared to bare root stock, since the root system is intact and many fine roots are on the outside of the root ball (Harris & Gilman, 1993). Under drought conditions, seedlings in containers have higher field survival in sites with drought conditions (Grossnickle, 2005 and references therein), which may have a significant role in many Australian out-plantings. Overall, containerized seedlings have a better survival rate, are easier to plant, have more immediate growth response benefits, and are cheaper to produce and plant than bare-root seedlings (Landis et al. 1990). For example, Survival increased by 22 % in *Pinus palustris* seedlings grown in container stock compared to bare-root seedlings across 21 studies (South *et al.*, 2005).

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). After 10 years of field growth container grown seedlings of ponderosa and Jeffrey pine seedlings grew better than bare-root seedlings, with mean height and diameters (McDonald, 1991).

both height and diameter

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).This is important for nursery decision making, as although bare-root seedlings must additionally compete for resources belowground, the same optimal seedlings size conclusions still apply for both stock types (Aphalo & Rikala, 2003). In terms of roots to shoot balance, bare-root seedlings have been found to be larger than containered seedlings with a greater S:R. (Rose & Haase, 2005), due to the removal from planting beds.

*bareroot tree balance* + pruning practice + growing density + root wrenching This loss produces an imbalance in the shoot to root ratio and reduces the chance for successful field establishment and competitive growth of seedlings (Schultz *et al.*, 1990).

Based on the methods of removal, bare-root seedlings have shoot:root of 3:1 or less compared to container seedlings with a shoot:root of 2:1 or less (Haase & Others, 2007). 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 R:S and increasing large containers stock types (Grossnickle & El-Kassaby, 2015). As a result, nursery tree stock standards should be more reliable between these two types..if they work at all (can be shown to be accurate)

Root morphology likely different (cites from davis2005). + root direction + size and shape

### The container design used for tree stocktypes has a major influence on root systems (Landis *et al.*, 1990, Chapman & Colombo (2006)), and this tree balance

Trees grown in containers have been shown to develop root deformations (Ortega *et al.*, 2006), thus pruning managements (manual or container) is now common practice in managing healthy root systems during nursery production. There are numerous container types and treatments applied to containers aimed at natural 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 in an attempt 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). For example, red maple seedling height and diameter were found to similar across a large range of container types after 24 weeks, however, root deflection was decreased in containers which air or chemically pruned roots compared to standard plastic containers (Marshall & Gilman, 1998).Containers that auto-prune roots may inadvertently alters natural patterns of tree biomass investment (Climent *et al.*, 2008), thus affecting root to shoot balance during nursery production. Although roots deflected inside containers are commonly associated with tree instability, little is known about root form in large nursery containers (Gilman *et al.*, 2010).

# container volumes (surrogates for belowground)

Across a longer timescale it is likely more economical to purchase and plant an expensive tree with a higher rate of survival that a less expenseive tree with a higher mortatiliy rate (Miller *et al.*, 2015). In terms of nursery production this often refers to larger trees grown in larger container volumes. In Australia these trees are commonly referred to as "" tree stock.

vigor is related to the volume of soil readily accessible to growth of the root system (Chalmers, 1988; Cockroft and Olsson, 1972). Available rooting volume represents this ..., and in container growth media is a finite spacial resources for growing root systems. Independent of nursery practices including growing media, watering or fertilization, gradients of rooting volume gradient may mechanically impedes whole plant growth and physiological activity (McConnaughay & Bazzaz, 1991; Climent *et al.*, 2011)*get other cites*

Volume is one of the most obvious and important characteristics of a container as the larger the container the larger the seedling that can be produced, however, optimum container sizes can vary by species, growing density, environmental conditions and growing season length (Tsakaldimi *et al.*, 2005). Container depth will determine root system growth and tap root length, which will aid in soil colonization of deep soil horizons (Chirino *et al.*, 2008). Nelson (1996) suggested that improved after-planting performance of eucalypt seedlings produced in larger containers was due to differences in root architecture. A review of the pot size effect on woody species found that increasing container volume generally improves biomass production (Poorter *et al.*, 2012). For the nursery industry, this may have important consequences for subsequent tree growth following out-planting.

The use of different containers types and volumes has been shown to have morphological consequences. Commonly,positive associations with including height, RCD and total mass are found with increasing container size (Ran *et al.*, 1992; Hsu *et al.*, 1996; Peterson, 1997; Mariotti *et al.*, 2015). Thus, larger tree stock size in nursery production is often equated with an increased morphological quality (Simpson, 1996). Cork oak seedlings also had similar height and diameter after a 10 month nursery period in shallow and deep containers, yet deeper containers had more larger tap root and near double fine root biomass (Chirino *et al.*, 2008). Importantly, these degree of these developmental differences in growth across different container volumes are likely differ by species (Climent *et al.*, 2011). Interestingly, South & Mitchell (2006) showed that RCD too small and too large negatively affected out-planting survival, with the large container stock probably decreased performance due to root binding.

The size of containers plants are grown in prior to out-planting has also been shown to significantly impact field shortly months after planting (Close *et al.*, 2006). Seedlings raised in larger volume containers may affect post-planting performance through reduced handling damage at planting, higher root:shoot ratio than smaller containers, and higher total biomass with a similar root:shoot ratio compared to plants in the different containers (Close *et al.*, 2010). Larger container volumes can lead to increased field performance via increased2012pot height, diameter and nutrient content in *Pinus pinea* seedlings, with a possible optimal relationship of container depth:diameter or 4 (Dominguez-Lerena *et al.*, 2006). However seedlings out-planted from very large containers may also undergo water stress as large foliar water demands may outweigh root uptake potential during early growth (Lamhamed *et al.*, 1997). This is indicative of a less developed root system, and can restrict the capacity for nutrient and water uptake (Will and Teskey I997). Seedlings in larger containers will be larger than those of smaller containers, yet whether this leads to increased survivorship in trees in the years following out-planting is still uncertain.

As advantageous as larger container volumes appear to be, this does not necessarily fit in with the economics of nursery production. Producing high quality seedlings in smaller containers, grown at high densities, is more advantageous to profit. Thus, the container type can influence the economics of planting programs (check nesmith/pinto2011). The shape and size of containers exert serious constraints on the growth of roots and their function, especially in hardwood species, adversely affecting seedling development. (Wilson *et al.*, 2007; Mariotti *et al.*, 2015). If a container size is too small, then root restriction can will inhibit the ability of root system to supply adequate water to shoots and will negatively affect seedling C gain (Will & Teskey, 1997). Although proper root to shoot balance will be essential for out-planting success the size of the container used for different stock types may more likely depend on nursery practices to maximum growth, yield and profitability.

Although large stock is expensive to produce, it is likely to be more cost effective to plant because of its higher probability of success and the correlatively reduced numbers of trees required to meet a given stocking goal (Johnson, 1989). This concept, however, arises from large scale afforestation and plantation needs. It is likely that the current increasing demand for urban and landscape trees will fit beneficially into this criteria. Green space demands will instead consists of a different set of conditions, revolving around species choice, etc.. This will replace the high volume, single species, production of tree stock that will have different economic consequences. (more species, each of high quality within a nursery). A central issue then arises around dispatching, translating tree stock to larger container, or culling to maintain proper balance while managing cost, time and nursery space.

demand for different sizes for landscape use = different container volumes

*does pot volume affect root:shoot in trees?* A large question that remains is to the degree of correlation between tree stock balance and if rooting volume accurately represents the belowground status of a seedling. How root to shoot balance and subsequent field performance is altered by growing tree stock in larger containers is a fundamental question intersects quality nursery production and economics. First, it should be determined the degree to which larger containers actually improve overall seedling quality. Then, economic studies must quantify if increased production and plantation costs linked with larger containers could be compensated by higher field success (Climent *et al.*, 2011). Increasing container volume increased the root:shoot ratio at a given seedling height for Eucalyptus globulus across 10 nurseries, (Close *et al.*, 2003).

Commonly, an increase in plant size with larger containers is realized through increased shoot growth which decreases the R:S (Climent *et al.*, 2011 *villar?, neeed others*).

Different container volumes did not affect R:S in silver birch (Aphalo & Rikala, 2003), Quercus robur and Juglans regia seedlings (Mariotti *et al.*, 2015) or wax apple (Hsu *et al.*, 1996).

For Picea glauca seedlings S:R increased nearly two fold from 2.3 to 4 after 20 weeks from from 10cm3 - 524cm3 container volumes (Carlson & Endean, 1976).

R:S did not shift in western larch seedlings across volumes from 111ml to 207ml (Aghai *et al.*, 2014)

?why---refer to poorter

\*does R:S differ significantly by species, stock type or climate??? (KEY QUESTION)

There appears to be a co-ordination of shoot and root growth as the soil volume available for root growth increases (Menzel *et al.*, 1994)

Root volume provides a simple, accurate, and non-destructive characterization of root system morphology (Jacobs *et al.*, 2005), however the question remains over whether container volume can be used as a surrogate for estimating root volume and thus root system size. If rootball occupancy has meet the standard, then can container volume be used to predict aboveground growth? (will depend on the knowledge of age/transplanting time at time of sale).

## how management practices come into play

Nursery cultural and silvicultural practices have a strong influence on seedling performance immediately after planting (Grossnickle, 2012). This boils down to the goal of providing tree stock that have the highest capacity for survival once they leave the nursery. Seedling size in the nursery can be manipulated by the length of the growing season imposed by the timing of seed sowing (Close *et al.*, 2006). Additionally, the length of the growing season can vary across different climates zones, such as those present across Australia....what this means for evergreens, 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).

*irrigation (amounts and hardening)*

*fertilization (amounts and deprevation)* Proper fertilization of nursery tree stock is essential for high seedlings quality, however, the degree of fertilization may also impact the production of carbohydrates. Alleviation of nitrogen stress on seedlings may result in less fixed carbon allocated to storage (Green *et al.*, 1994; Holopainen *et al.*, 1995), which may then impact the availability of starch pools for new growth following out-planting or the ability to synthesize herbivory defense compounds. In addition, nutrient deficiencies (ie nitrogen or phosphorus) in nursery trees can cause decreases in leaf chlorophyll constant and the subsequent negative impact on leaf physiology can also lead to decreased carbohydrate production, tree slenderness, seedling height and RCD in nursery trees (Trubat *et al.*, 2010).

Shoot:Root ratio has also been shown to be responsive to fertilization regimes, with higher S:R with increased nutrient supply for several tree species (Villar-Salvador *et al.*, 2004)(Green et al., 1994; Holopainen et al.,Canham et al.,1996 1995; Graff et al., 1999), usually manifesting as increased shoot growth and not reduced root allocation. Commonly, the reduction of belowground resource limitation by fertilization and irrigation leads to increase mass partitioning to shoot growth compared to root growth, thus decreased R:S (McConnaughay & Bazzaz, 1991; Canham *et al.*, 1996; Luis *et al.*, 2009; Jackson *et al.*, 2012) *more*

Consequently, the management of fertilization of tree stock throughout the nursery period may have important consequences for seedling root:shoot balance, as well as future seedling establishment. The sensitivity to the positive effects of fertilization and irrigation practices on growth rates of seedlings, however, will likely vary by species (Canham *et al.*, 1996). Additionally, if seedlings are intentionally nitrogen hardened before sell will reduce seedlings traits including height, rcd, leaf area and rgp (Trubat *et al.*, 2008), but may improve their field performance in semi-arid or drought sites (Trubat *et al.*, 2011).

*media* Different growing media can affect root system development and thus have down stream effects on out-planting seedling success (Heiskanen & Rikala, 1998). The use of different growing media may interact with climate and nursery practices to affect root development and thus tree balance. Growing media imposes limitations on water and nutrient availability and thus seedling uptake.

Beyond survival, management strategies need to be developed to successfully care for trees in a harsh urban environment, particularly with the use of skeletal soil material profiles (Loh *et al.*, 2003). ---interaction between media before and after

*planting density* seedlings raised at high densities self-shade that potentially pre-disposes leaves to photo damage due to the rapid change in exposure to light after transplanting (Close, 2012).

*root pruning* Proper root-pruning can allow any shape of container to produce a plant with the potential to develop a natural root form (Nelson, 1996). 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, decreading root morphological defects (kinks, j-rooting) [gilman2010root]. As such, root pruning is commonly performed when transplanting into containers and represents an active management practice to increase the amount of resource absorbing roots and thus seedling quality. Once out-planted, tree stability and establishment also improve with reduced root defects from active root pruning (Gouin, 1983; Gilman *et al.*, 2009).

Plants grown in common smooth-sided containers can have the higher percentages of deformed roots compared (Amoroso *et al.*, 2010), thus nurseries often physically root prune tree stock during production.

In addition, a multitude of studies have shown the negative effects of root restriction can have on the physiology, growth and R:S balance in trees. Root restriction resulting from limiting container volume can cause..... *(borrow from eucpve)*. Management of root pruning can alleviate these negative feed-backs during nursery production.

# effects of environment on nurseries and seedling performance

Different environmental conditions across nursery locations can have important influences on functional traits of a common seedling type (Mollá *et al.*, 2006). Thus, assessments of seedling quality can also vastly differ among seedlings taken from different nurseries, even when they are produced from the same seed lot, over the same growing season (Pinto *et al.*, 2011a).

ex. affects on cold hardiness (Pinus radiata and in Pseudotsuga menziesii (Menzies et al., 1981; Schuch et al., 1989) ex. drought tolerance in meditaranian climates [ ex. possible differences in length of growing season/day length

q.ilex root growth, frost resistance and drought tolerance attributed to climate in which seedlings were grown (nursery location) (Mollá *et al.*, 2006).

Different nursery thermal regime can have an effect on survival of seedlings (Aleppo pine), but not all (Holm olk) (Pardos *et al.*, 2003).

Temperature extremes limit growth and can cause seedling mortality, with larger diameter seedlings having greater insulating corky tissue to dissipate excess heat (Cleary *et al.*, 1978).

Often studies related on overwintering of deciduous tree stock or coastal versus inland nurseries in Mediterranean climates. In these circumstances, seedlings can become pheonologically out of phase if dormancy is affected by temperature during over wintering. Geographical differences in nurseries will thus likely play a large role in growth of similar stock types, especially regarding temperature. Management practices include N hardening to increase drought tolerance (Villar-Salvador *et al.*, 2004; Trubat *et al.*, 2008)

This potential impact of climate on nursery production in Australia has been relatively unexplored, in which tree nurseries propagate plants from tropical to temperate climates. If differing climates affect either morphological or physiological parameters of seedling health then the extrapolation of results across sites will be less accurate. This raises the question of how large of an impact does climate variability on nursery stock tree growth. Much of the past research has focused on growing season cycles and dormancy periods in temperate climate zones. Although much can be drawn from this research, it does not fully represent the growing climate/species (evergreen) patterns of Australia.

**Here sum up nursery culture and climate by saying need to include co-variates when evaluting seedling quality across Australia.**  
 **Next say that age, time since transplant and species must also be accoutned for.**

# Evaluating the Australian standard:

little emphasis on physiological assessment in the nursery. The question remains on whether the morphological indices defined in the standard represent proper root:shoot balance for the most common and widely distributed stock types in Australia. The newly adopted AUS standard assess tree balance with 'Size Index' as a function of container volume or rootball diameter for containerized or bare-root tree stock, respectively. Size index is calculated as the product of height (m) and caliper (at 300 mm), and is expected to represent the physical bulk of the tree aboveground (Clark, 2003). A cost effective sampling procedure is needed, limiting destructive sampling, as every seedling to be out-planted cannot be measured or assessed easily with current techniques (Puttonen, 1997).

Tree root to shoot balance is commonly believed to play a major role in water status of an out-planted seedling, and plays a critical role in survival in droughted field conditions. In urban systems, this balance may critically define the success of planted tree stock as (hotter drier cite). Drying is the most stress-causing factor influencing the young seedlings (Wrzesiński, 2015), requiring proper root to shoot balance for seedling success.

One major issue is that prevailing temperatures and climate, as well as different irrigation and fertilization regimes, will affect seedling quality during nursery production (Mattsson, 1997).

Rob bodenstaff here

## Tree balance in other national nursery standards?

In the **European technical & quality standards for nursery stock** the container and plant size are expected to be in reasonable proportion (*European techincal & quality standards for nusery stock*, 2010). In this standard only minimum height for container stock in specified, with no specific guidelines for large container sizes. The Americanhort's **American standard for nursery stock** in 2014 acceptable ranges for plant height and rootball dimensions based on caliper/height specifications (*American standard for nursery stock*, 2014). In the **Canadian Standard for Nusery Stock** containerized stock is graded with an acceptable range of either height or canopy spread for different container sizes (*Canadian standards for nursery stock*, 2006).

Alternatively, the "Size Index" specification in AS2303 is meant integrated measurement of aboveground bulk of the tree relative to the size of the container (Clark, 2003; *AS 2303:2015 Tree stock for landscape use*, 2015). This specific quantification of tree balance marks an important distiction between AS2303 and seedlings quality standards from other major market countrues in with the evaluation of tree balance.

Additionally, each of these other standard classify tree stock into groups (i.e spreading, upright, evergreen , deciduous), with quality specifications for each group. The AS2303 simplifies quality assessmens by including only one guideline for all tree stock.

## Capturing inherent variation within nursery tree stock

## Error in readPNG("images/variation\_concepty.png"): unable to open images/variation\_concepty.png



## Error in rasterImage(climate2, xleft = 0, ybottom = 0, xright = 1, ytop = 1): object 'climate2' not found

*natural variation* Intraspecific variation refers to phenotypic variation that naturally occurs within-species. In production nurseries, this effect is a curious issue as the seed source for individual stock types is.....

Or even between provenances of a single species, relying on additional information on seed origin.

*species variation* 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). As plants have developed different strategies to uptake resources and to utilize resouces to maximize growth in a specific way, large varition in size, shape and growth rate exists among tree speices. As a result, plant growth rate heavily depends on this biomass partitioning to different parts, expecially to leaves. For example, evergreen species have ....compared to deciduous species [].

Species with high growth rates are more competitive in acquiring resources, whereas species with low growth rates are more conservative with the scarce resources they have obtained (Grime, 1977; Berendse and Elberse, 1989; Reich et al., 2003b; Poorter and Garnier, 2007).

poorter 2012..

relates to as2303= does it capture this (much greater than within species variation) It entirely possible for certain morphologies to commonly fall out of exceptable range if SI is too narrower. As with other nursery standards, should stock type groups be assessed differently in order to accurartely assess qualtiy within different morphotypes?

types = evergreens (spreading or upright)

Although parameters such as height diameter have been shown to strongly correlate with root growth and field success, how will species differences affect the ability to set minimum/maximum standards for the entire industry. Does SI account for large variation between types with different forms?

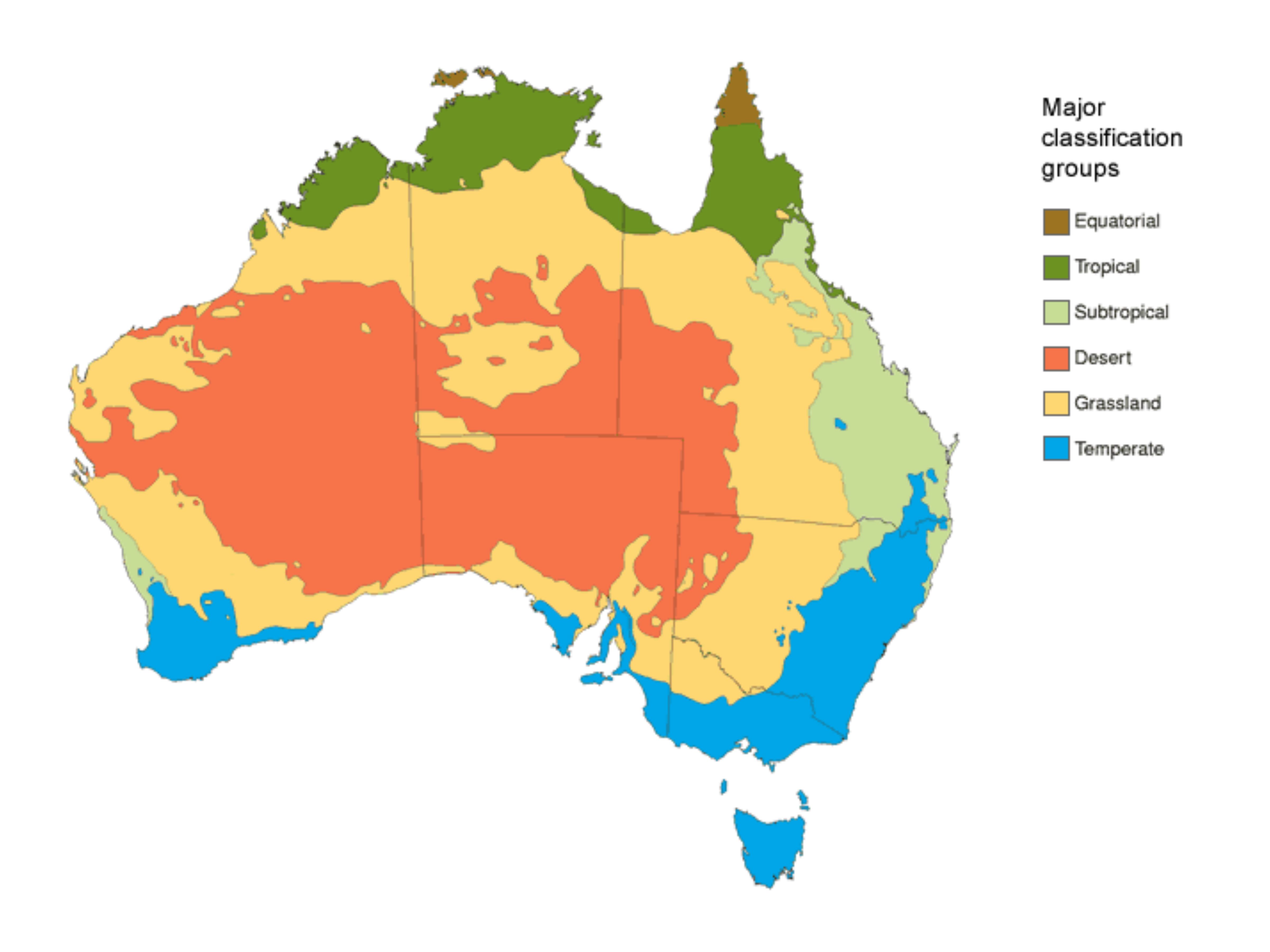
### What is the species effect? Is root to shoot balance conserved? fast, slow, native -non native, temperate decidous??? Can stocktypes be grouped?

*nursery practices* 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 too old with root binding and defected root systems (Ford, 2014). Container size in relation to plant size will vary with geographical location and grower established practice [{@canstand](mailto:%7B@canstand)}

*climate* (potential impacts on indices) Due to the large size of the Australian continent, there are six different climatic zones and two distinct seasonal patterns [bom.gov]. It is recognized that climatic conditions in different sections of the country produce plants of different caliper height proportions and variance also exists in caliper height proportion from species to species.

The climate of Australia means that many tree stock are container grown in open environments, and thus are exposed to ..... Seedling growth is is heavily influenced by levels of moisture, temperature, light, and nutrition (Cleary *et al.*, 1978).

stats: range of temp and precip (plants grown and out-planted in variable locations) (these are interdependent variables) Australia already represents an area of high aridity, nutrient soil deficiency(P), etc. It is also designated as being more susceptible to extreme climate events (IPCC). In this sense nursery standards developed to deal with an already inhospitable out-planting environment Additionally, if successfully these standards could possibly be used as a surrogate for understand the needs of other countries who are or will be facing future hotter and drier climates.



# Outcomes

As information is gained with local nurseries, recommendations and size specifications for containerized plants are likely to change to more accurately match site, species, and planting time to individual stock type (Nelson, 1996). Operational quantification of some morphological variables are not practical for nurseries to implement on a large scale, but if superior predictors can be identified it may be possible to modify nursery cultural techniques to improve quality (Wilson & Jacobs, 2006).

In should be explicitly mentioned that robust survival and field establishment experimental trials should be undertaken in accordance with each current version of the Australian standard. Importantly, this must include aspects of that test not only the variable climate across Australia but urban environments as well. This will ensure that the current and future visions for urban greening are met and that the tree nursery growers remain the strength of partnership between the .....

Aghai MM**,** Pinto JR**,** Davis AS. **2014**. Container volume and growing density influence western larch (Larix occidentalis Nutt.) seedling development during nursery culture and establishment. *New Forests* **45**: 199–213.

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.

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

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.

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

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.

***Canadian standards for nursery stock***. **2006**. Ontario, Canada: Canadian Nusery Landscape Association.

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**,** Bail I**,** Hunter S**,** Beadle CL. **2006**. Defining seedling specifications for Eucalyptus globulus: effects of seedling size and container type on early after-planting performance. *Australian Forestry* **69**: 2–8.

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 textit{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.

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.

Dominguez-Lerena S**,** Sierra NH**,** Manzano IC**,** Bueno LO**,** Rubira JLP**,** Mexal JG. **2006**. Container characteristics influence Pinus pinea seedling development in the nursery and field. *Forest Ecology and Management* **221**: 63–71.

***European techincal & quality standards for nusery stock***. **2010**. Lochristi, Belgium: European Nurserystock Association.

Ford C. **2014**. Improving field survival of pine seedlings and cuttings: the Sappi Plant Quality Index{copyright}. *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. **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**,** 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.

Harris JR**,** Gilman EF. **1993**. Production Method Affects Growth and Post-transplant Establishment ofEast Palatka’Holly. *Journal of the American Society for Horticultural Science* **118**: 194–200.

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. Seedling physiology and reforestation success. 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.

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, oH.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. **1989**. Growing hardwood nursery stock for planting on forest sites with special regfernce to northern red oak.

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.

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.

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**,** Others. **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**,** 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-Rodr’iguez 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.

Menzel CM**,** Turner DW**,** Doogan VJ**,** Simpson DR. **1994**. Root shoot interactions in passionfruit (Passiflora sp.) under the influence of changing root volumes and soil temperatures. *Journal of Horticultural Science* **69**: 553–564.

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 symp.: Sept.6–7.

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

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.

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

Pinto JR**,** Others. **2011**. Morphology targets: What do seedling morphological attributes tell us? *Pinto, Jeremiah*.

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**,** 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.

Ritchie GA. **1984**. Assessing seedling quality. In: Duryea ML, In: Landis TD, eds. Forestry nursery manual: Production of bareroot seedlings. 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.

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

Simpson DG. **1996**. Nursery growing density and container volume affect nursery and field growth of Douglas-fir and Lodgepole pine seedlings. Forest and conservation nursery associations: 1994 national proceedings. DIANE Publishing, 105.

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**,** 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.

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

Struve DK**,** Others. **2009**. Tree establishment: a review of some of the factors affecting transplant survival and establishment. *Journal of Arboriculture* **35**: 10.

Thompson BE. **1985**. Seedling morphological evaluation: what you can tell by looking (M Durvea, Ed.). *Evaluating seedling quality: principles, procedures, and predictive abilities of major tests*: 59–71.

Tinus RW. **1974**. Characteristics of seedlings with high survival potential. Proceedings of the north american containerized forest tree seedling symposium. great plains ag. council publ.276–282.

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**,** Enriquez E**,** Rubira JP. **2004**. Nursery cultivation regimes, plant functional attributes, and field performance relationships in the Mediterranean oak Quercus ilex L. *Forest Ecology and Management* **196**: 257–266.

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

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.

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.