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 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 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 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 tree nurseries to provide 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 planting stocks with uniform morphological characteristics (Puttonen, 1997). In 2015, the Australian nursery industry adopted a new standard to assess the qualtiy of tree stock for landscape use (AS2303:2015). 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 on in attempts 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), however the quality of tree stock is often 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 the culmination of all the practices that have preceded 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, 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.

## Review of the 'target seedling concept'

Nursery stock can be graded by both morphological and physiological characteristics, but these characteristics must be related to out-planting performance (Landis, 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, 2011). As cheap and quick physiological tests are lacking, morphological and physiological assessments are rarely conducted together (Hobbs, 1984; Pinto *et al.*, 2011a). 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 evolved into 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 responese 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 address stock quality are: height, diameter and root system size (Thompson, 1985; Mexal & Landis, 1990; Rose *et al.*, 1990; Haase, 2011; Pinto, 2011). Consequently, seedling quality represents how each of these 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). Thus, 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).

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. 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). Indices combining various morphological traits (i.e. root:shoot, height:diameter) have therefore been adopted to better assess overall seedling quality.

# mini-Review of common morphological indices

## Aboveground (Height, Diameter/Calliper)

Tree nursery standards from various countries generally focus on the 3 core parameters (height, diameter and root system size) 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). Metrics of shoot system size relate how available soil water and nutrients, competition for light limited 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 having 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

## Primary stresses affecting nursery tree stock

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.

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). 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. Minimizing transplant shock is highly relevant issue for tree stock in Australia. Planned increases in urban green spaces combined with varying climate and soil constraints that typically define Australian ecosystems will require tree stock from production nurseries to have appropraitely balanced root and shoot systems. It is for these reason that tree balance criteria are now specified in quality assessments of Australian tree stock (Clark, 2003; **???**).

# 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 (**???**). 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 (**???**). 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 (**???**).

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; **???**). 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

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*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?

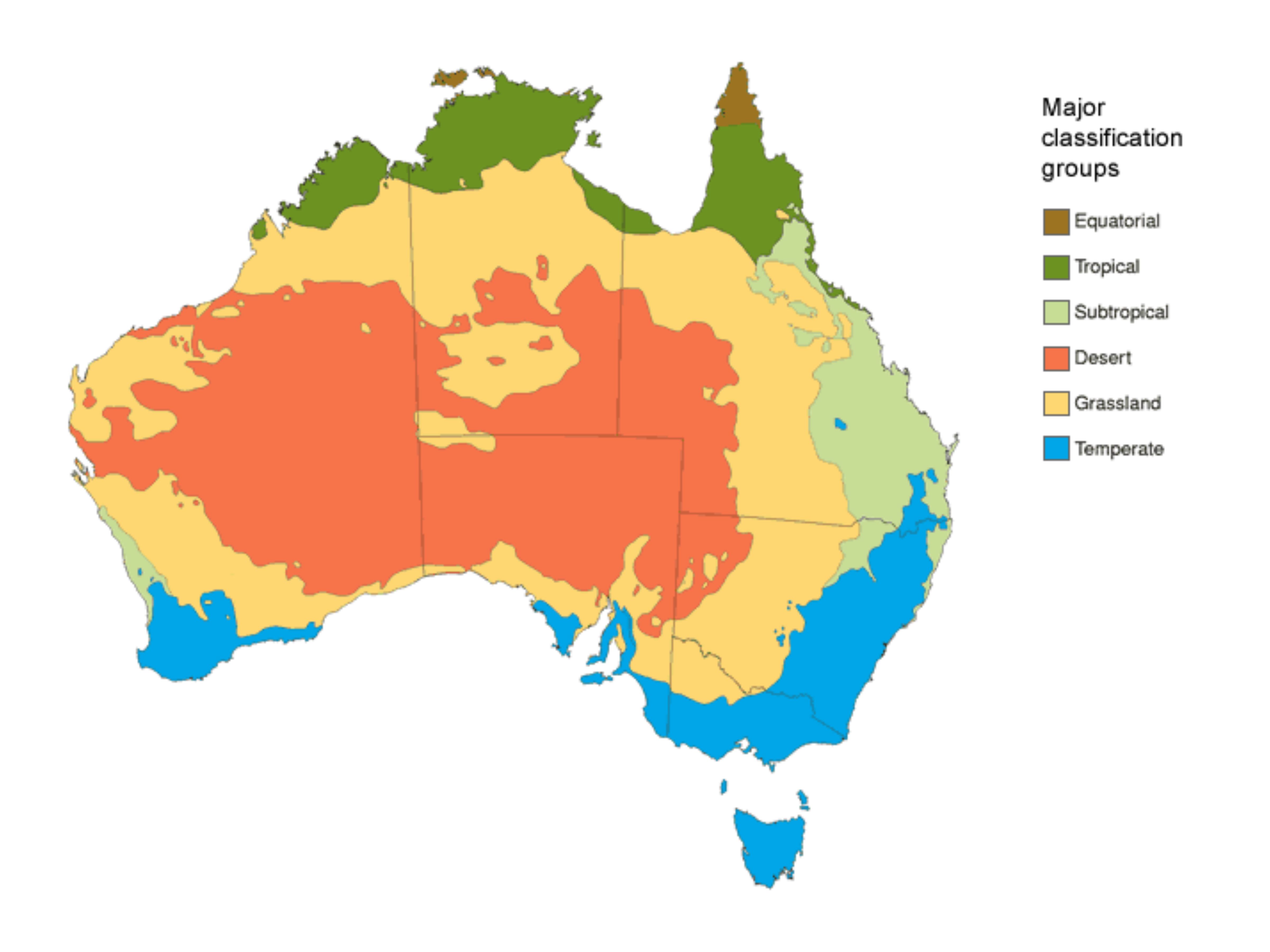
### What is the species effect? Is root to shoot balance conserved? fast, slow, native -non native, temperate decidous??? Can stocktypes be grouped?

*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 .....

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