Horticulture Innovation Australia

Final Report

Evaluation of Nursery Tree Stock Balance Parameters

Mark Tjoelker
University of Western Sydney

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Fax: (02) 8295 2399

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Summary

Root to shoot balance in nursery tree stock is thought to represent an important quality characteristic and contributing factor in tree growth, form and outplanting success in the landscape. Yet specifying root to shoot balance criteria and standards has been problematic owing to a lack of information on biological variation among species, nursery production practices and the role of climatic influences on shoot morphology and growth. In Australia, tree stock quality assessment criteria are specified in guidelines in the *Australian Standard: Tree Stock for Landscape Use* (AS 2303:2015), which at the time of publication recognised the need for data on root to shoot balance in trees produced in nurseries throughout Australia. Thus, the objective of this research was to quantify the role of species and climatic region in influencing root to shoot balance of grower tree stock in order to enable an evaluation of the tree stock balance assessment criteria within the standard.

While nursery practices, such as watering and fertilizer amendments, mitigate limitations to tree growth and function, climate and species are nonetheless important factors governing natural variation in nursery tree stock. Thus, we aimed to test if climate, species or region-specific differences in root to shoot balance exist and their potential importance in informing quality assessment criteria in AS 2303. Incorporation of evidence-based research on tree stock balance has the potential to increase grower and consumer confidence in AS 2303 as the industry standard and further drive product quality through its adoption by growers, specifiers and purchasers of trees grown for landscape use. Consequently, this research and it outcomes target wholesale tree production nurseries in Australia and stakeholders in the landscape industry and urban greening projects, including councils, landscapers and arborists.

Between April 2016 and January 2017, a team from Western Sydney University travelled to each mainland state and territory, visiting 23 wholesale nurseries and collected data on nearly 14,000 containerised trees, sampling 159 tree varieties. The team compiled an extensive database of tree height and calliper measurements used to calculate *Size Index* across all of Australia's major landscape tree market regions. In addition, a worldwide literature review was undertaken to investigate the factors affecting root to shoot balance in containerized trees and the importance of root to shoot balance for outplanting success.

Based on the research findings, the current specified range of *Size Index* in relation to container volume in AS 2303 does not adequately capture the natural variation across the large diversity of 'ready for dispatch' trees in Australian nurseries. Of the measured, standard-conforming trees, only one-third fit in the specified range of *Size Index* values across all container sizes (18 to 3000 L). Of the individual trees that fell outside the specified *Size Index* range, twice as many were below than above the standard. The largest sources of variation were detected in small to medium-sized containerized trees. Importantly, at a given container size, deciduous trees had a higher size index than evergreen trees. This simple categorization appears to hold true across several distinct growing climates and many of tree species that are produced in Australian tree nurseries. As root to shoot balance determines tree structural integrity and regulates key physiological processes, we recommended that tree stock balance criteria remain an integral part of nursery tree stock quality assessments. However, modifications to the current AS 2303 tree stock balance criteria are deemed necessary to ensure that quality assessments accurately describe the natural biological diversity of tree stock produced in Australia. This rich data set, specific to nursery grown trees in Australia, can be used to improve standardized quality assessment criteria.

Keywords

Australian standard for tree stock for landscape use (AS 2303:2015); calliper; container volume; height; nursery industry; root to shoot balance; size index; tree stock

Introduction

The '202020 Vision' initiative aims to increase urban green space by 20% by the year 2020. This new initiative has the potential to drive market growth in tree nursery production for landscape use, introducing challenges and opportunities for the Australian tree nursery and landscape industry. Challenges include problems in establishment and survival of newly planted urban trees (Nowak *et al.*, 2004; Miller *et al.*, 2015) and meeting the rising demand for tree stock that can endure increasingly harsh environments. Hot and dry conditions in Australian cities, inconsistent irrigation, infertile soils, pests, diseases and urban heat islands threaten the survivability and vigor of urban trees and the success of green infrastructure (HIA, 2016). Additionally, species choice for urban planting sometimes neglects considerations of stress tolerance 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 site conditions.

Planting, establishment and monitoring of trees in urban environments requires considerable investment by local Councils (Lawry & Gardner, 2001). Thus, tree stock quality and outplanting success are increasingly important. Selecting the appropriate cultivar, properly preparing the planting site and management of outplanted trees is of little consequence if the quality of the planted tree stock is initially poor (Moore, 2001). Confounded with the demand for uniform high quality trees is that variability within tree stock is a near certainty during nursery production. This variability presents a unique challenge for nurseries attempting to produce tree stock with uniform morphological characteristics (Puttonen, 1997). In April 2015 the "*Australian standard: Tree stock for landscape use*" (AS 2303) was adopted as the industry standard to enable assessment of the quality of tree stock across Australian nurseries (Standards Australia Limited, 2015). This standard was designed to assess above- and belowground characteristics of production tree stock for all stages of growth. Although use of AS 2303 is not mandatory, it is likely to be increasingly called upon to ensure quality at the point of sale with the aim of minimizing risks of outplanting failure or poor form and growth with new landscape and green infrastructure projects.

Proper balance between root and shoot systems is critical for establishment of outplanted trees as balance encompasses the initial structural stability of a tree and the relationship between water uptake and loss. In AS 2303, an aboveground bulk size parameter (*Size Index*) is calculated as the mathematical product of stem calliper (mm) at 300 mm and total tree height (m). Aboveground *Size Index* is then compared to the size of the container at dispatch, where container volume (L) reasonably represents root system size, owing to complete occupancy of the rootball. Minimum and maximum acceptable values of *Size Index*, generalized for all species, are specified for the large range of container volumes used in Australian wholesale tree nurseries. If use of *Size Index* and its relationship with rooting volume provides an accurate assessment of tree stock balance, it offers a tool for growers and buyers of landscape trees to assess product quality and uniformity and ensure or potentially enhance the performance of outplanted trees. Many current international nursery tree standards include assessment criteria for different classifications of tree stock (i.e. spreading, upright, evergreen, deciduous, etc.), whereas AS 2303 provides a single guideline for all tree stock. If large natural variation in *Size Index* occurs across species, climate regions or in response to nursery practices, the currently specified acceptable values in AS 2303 may not adequately capture tree stock balance. Likewise, if variation in height and calliper and thus *Size index* is quantifiable in terms of tree stock type or climate zone, then this information may be useful in revising or tailoring acceptable ranges in the standard to provide more refined guidelines.

Summary of literature review

Tree quality is the foundation of outplanting success and the capacity for growth following establishment. Evaluating nursery seedling quality is necessary to understanding seedling development and the capacity for growth after outplanting (Wakeley, 1954), yet the quality of tree stock is often assessed inconsistently (Haase, 2008). A primary goal of seedling quality assessments is to quantify attributes which accurately assess the condition and potential for growth of different stock types (Wilson & Jacobs, 2006). As there is no single test which encompasses seedling quality, assessing a seedling is analogous to a physician conducting a multitude of measurements to characterize a patient's general health (Ritchie, 1984).

The main morphological attributes used to grade tree stock quality are: height, diameter and root system size (Thompson, 1985, Mexal & Landis, 1990, Rose *et al.*, 1990, Haase, 2011, Pinto, 2011). The quality of an individual seedling represents how each of these main attributes act together and influence one another (Wightman 1999). Assessments used to describe a quality nursery plant generally convert these core morphological characteristics into grading standards (Landis & Dumrose, 2006). When assessed individually, these parameters are known to exhibit large variation and are poor predictors of outplanting success. Combinations of root and shoot morphological characteristics, representing tree stock balance, should better assess seedling quality and predict future health of any nursery tree.

To become established, a transplanted nursery tree must generate a root system to support shoot growth that is comparable to a non-transplanted tree (Watson *et al.*, 1997). Proper root:shoot balance is also an essential index of plant water uptake capacity (root) to water loss (shoot) at the time of planting (Ritchie, 1984; Thompson, 1985; Grossnickle, 2000; Haase & Others, 2007). The challenge facing nursery growers is to optimize canopy growth while also ensuring that root systems are properly managed, especially as containerized systems can alter root system quality (Moore, 2001). However, parameters used to evaluate tree stock balance are likely affected by nursery practices such as container style, root system management, irrigation, fertilization, root pruning and growing media, as well as prevailing climate and time since re-potting. Tree quality grading may differ among similar species from different nurseries, even when they are produced from the same seed source and over the same growing season (Pinto 2011), which makes the development and implementation of unified tree stock balance assessment criteria challenging.

Literature review aim

In preparation for our field research, we sought background information on nursery tree production practices regarding management of root to shoot balance and its quality assessment. Thus, our aim was to acquire baseline information on root to shoot balance of tree planting stock and performance metrics from the peer-reviewed scientific and trade literature. To achieve this aim, we consulted the world-wide literature in horticultural and forestry sciences to compile information on the metrics used to assess root to shoot balance and industry best practices in managing root to shoot balance of tree stock. We reviewed existing national and international standards for quality assessment criteria related to root to shoot balance of nursery tree stock. Both qualitative and quantitative data were extracted from the literature and formed the basis of an expert synthesis and review for the Australian tree nursery industry.

Field research aims

Our research aim was to evaluate root to shoot balance in wholesale trees nurseries across Australia through evidence-based, non-destructive measurements following all the aboveground and belowground assessment criteria at time of dispatch as specified in AS 2303. The principal questions that we addressed were:

(1) Does the evaluation of root to shoot balance in nursery stock via *Size Index* capture sufficient natural variation across the large diversity of 'ready for dispatch' trees in Australian nurseries?

(2) Which of the two components of *Size Index* (height, calliper) are the most variable across species grown and container volumes used during nursery production?

(3) In addition to within and among species variation, how much variation in *Size Index* (and its components) can be attributed to different growing climates and nursery practices?

Methodology

Nursery site

Measurement campaigns were completed at 23 wholesale tree production nurseries across each of Australia's continental tree production market regions between April 2016 and February 2017 (Figure 1.). Multiple nurseries were visited in each region, except for a single nursery in the Northern Territory, to collect data that provided both regional and national coverage. Batches of tree stock that were currently ready for sale were identified with nursery production managers at each site. From these batches, tree stock in containers ≥ 18 L were selected for measurements. Priority was given to tree species that were available in multiple container sizes. Additionally, the 30-year mean annual temperature (MAT) and precipitation (MAP) were obtained for each nursery site at a 1 km^2 resolution (http://www.worldclim.org/; Table 1).

Visual quality assessments and testing

Prior to data collection (explained below), an above and belowground visual assessment of morphological quality was completed for each pre-selected batch of tree stock deemed ready to sell. These assessments were conducted independently by the project team and thus consistently across all nurseries. Root to shoot balance measurements were completed only for batches that passed all criteria for the above and belowground assessments. In other words, batches that failed any above or belowground test were not assessed for tree stock balance. This methodology ensured that data collection was representative of trees possessing all the morphological attributes required by AS 2303 at dispatch.

To test each batch, a sample tree was randomly chosen to represent the batch as a whole. The aboveground visual testing criteria were completed on the chosen tree as specified by AS 2303 (see clause 2.2 Standards Australia Limited, 2015). Briefly, the chosen tree was required to be self-supporting, have a symmetrical crown, have healthy leaves and crown structure and be free of injury, pests and disease.

If the chosen tree passed all aboveground assessment criteria, then the belowground assessment of rootball occupancy and root form was completed. The specified belowground quality assessment was carried out differently for different container volumes as specified in AS 2303 (see appendix B Standards Australia Limited, 2015). Trees in ≤ 45 L containers were removed from the container to expose the entire rootball. First, rootball occupancy was assessed. To pass this test, 90% of the growing medium volume (medium + roots) must stay intact around the rootball. Second, the tree was checked for the absence of woody circling roots along the outside of the rootball. Third, a wedge shaped slice was removed from the rootball to determine if root defects were present inside the rootball. Lastly, a visual assessment was conducted for root defects (e.g. j-rooting) and proper root growth direction in an outward and downward direction from the point of initiation. For trees in > 45 L containers, the growing medium was removed from the top surface from the trunk to the container edge to sufficient depth to assess root form and check for root defects. Failure in belowground assessment testing was the most common reason for batch failure.

Aboveground parameters for tree stock balance assessment

Tree height and trunk diameter at 300 mm were measured on a subset of trees for each selected batch of tree stock that passed all above and belowground tests. Up to 45 trees were measured for batches in containers ≤ 45 L and up to 20 trees were measured for batches in all larger-sized containers, if available. The *Size Index* parameter was calculated as the product of height (m) and trunk calliper at 300 mm (mm) for each measured tree. Tree slenderness index was calculated as the ratio of height and trunk calliper.

Canopy traits

Parameters related to canopy structure were measured on a subset of up to 10 trees per batch, if available. Maximum branch length was recorded for the longest visible branch, which was then doubled to calculate maximum canopy spread for each tree. Total canopy length was calculated as the difference between total tree height and the height at which the lowest branch intersected the main stem. A “branchiness” parameter was calculated as the number of branches in a 30 cm interval along the main stem (trunk) from the initiation point of the lowest branch. A summary of all measured traits is provided in Table A1.

Data analysis

Differences in measured tree height, calliper and *Size Index* with container volume were analysed using mixed-effects models. In the statistical models, tree species and nursery were classified as random effects, constituting a representative sample of both the species that were grown and of the nursery sites in Australia. The effects of climate, nursery, species origin (i.e. native or non-native), tree functional type (i.e. evergreen or deciduous) and leaf and canopy traits on measured parameters were treated as either continuous or categorical fixed effects. *Size Index* values were standardized to remove the effect of container volume, allowing us to focus on variation in *Size Index* related to all other driving variables. Standardized values were calculated by dividing *Size Index* by container volume to the power of 0.81. The exponent value represents the slope of the regression between log-transformed values of *Size Index* and container volume. Mixed model analyses were performed in the statistical analysis platform R (R Development Core Team, 2016), with the 'lme4' package (Bates *et al.*, 2015). Explained variance (R^2) of mixed models was computed as in Nakagawa & Schielzeth (2013), in which the marginal R^2 represents variance explained by fixed factors and the conditional R^2 by both fixed and random factors. All tests of statistical significance were conducted at an alpha level of 0.05. The coefficient of variation for tree height and calliper was calculated as the ratio of the standard deviation to the mean of raw measured values.

Outputs

1. Literature review

A draft literature review document has been completed.

Campany, CE, MG Tjoelker, S Pfautsch, RA Duursma, MJ Aspinwall, D Thompson. A review of root to shoot balance in containerized nursery tree stock: nature vs nursery.

The document is prepared for publication in the peer-reviewed scientific literature. We plan to publish any resulting paper as open-access to ensure wide accessibility. In addition, we intend to publish extracts or an alternate version in trade journals relevant to the Australian landscape tree nursery industry to facilitate uptake and use.

2. Conference presentation

Tjoelker, M.G., 2016. An assessment of root to shoot balance in tree stock for landscape planting in Australia: Update on the trials for the tree stock standard. *Share the Vision: The Road Ahead.* Nursery and Garden Industry National Conference, Adelaide, South Australia, 15-17 February, 2016.

> *Prof. Mark Tjoelker and Dr. Court Campany attended the Nursery and Garden Industry National Conference in Adelaide, South Australia in February, where Prof. Tjoelker presented an update on the nursery tree stock balance project to industry growers on 16 February.*

3. Industry magazine coverage

Smith, K., 2016. NGIA Conference: Traveling the road from the mainstream to the fringe. *Hort Journal Australia* 8 (8), 6–7.

> *Prof. Tjoelker's talk at the NGIA National conference in February 2016 on the launch of the tree stock balance project was featured in the leading horticulture industry magazine in Australia.*

Nursery Papers November 2016 - Getting to the Root of Tree Planting, Nursery & Garden Industry, Australia. *Hort Journal Australia* 9 (5), 21-24.

> *This Nursery Paper provided a midterm update on the tree stock balance project and its purpose and progress on field visits to grower nurseries throughout Australia.*

4. Website

A dedicated project website is hosted by Western Sydney University and regularly updated by David Thompson. (http://bit.ly/TreeStocks)

5. Communication materials and activities

Steering Committee Meeting, Hawkesbury Institute for the Environment, Western Sydney University, 17 Feb 2017
Case Study Video: https://www.youtube.com/watch?v=wYB-42BHjFo
Results Infographic (attached)
Your Levy At Work article update 2 https://yourlevyatwork.com.au/tree-stock-request-to-vary-standard/

Your Levy At Work article 1 https://yourlevyatwork.com.au/data-to-bolster-nursery-standard-for-assessing-quality-tree-stock/
Facebook Post March 28: https://www.facebook.com/nurseryandgardenindustry/posts/1633734653303441
Facebook Post Feb 28: https://www.facebook.com/nurseryandgardenindustry/posts/1594189593924614
Facebook Video Release Feb 16: https://www.facebook.com/nurseryandgardenindustry/videos/1577361558940751/
Facebook Steering Committee Meeting and Field Tour Feb 15: https://www.facebook.com/nurseryandgardenindustry/posts/1576143489062558
Facebook Finished Surveying Post Feb 2: https://www.facebook.com/nurseryandgardenindustry/photos/a.298423000167953.81548.140591102617811/1560369913973249/?type=3&theater

6. Online tool

An online tool is presently under consideration for ongoing development as part of our post-research activities and continued communication and engagement with the nursery industry. As noted in the contract, it is envisioned that the online tool would serve growers, stakeholders and consumers in the use and application of the industry standard AS 2303: 2015. Given the potential for changes to the standard based on independent research generated through this project, the tool and associated "how-to-guide" for application of AS 2303 is planned for completion in the next 12 months with further consultation with the industry.

Outcomes

Observation-based information on root to shoot balance was acquired on tree planting stock across contrasting regions of Australia and all major markets for nursery-grown landscape trees (Table A4). This information was compiled into a database which can be used to inform current and future decision making regarding standardized tree quality assessments for Australian nurseries. As intended, this research enables evidence-based revisions of tree stock balance assessment criteria within the *Australian Standard AS 2303:2015 Tree Stock for Landscape Use*. The nursery levy-funded research provides a pathway to improved assessment of tree stock quality nationwide. An evidence-based standard has the potential to enhance producer and consumer confidence in tree stock quality and further drive product quality and market growth.

The field research campaigns enabled engagement with Nursery and Garden Industry Australia members, specifically wholesale tree nurseries. Outcomes included nationwide promotion of the use of AS 2303 for morphological quality assessments of tree stock, including nurseries that had previously not utilized or were unaware of AS 2303. A number of wholesale nurseries have not yet transitioned from using "*Specifying Trees: A Guide to Assessment of Tree Quality*" (1996) to AS 2303 for tree stock quality assessments. One important outcome of engagement with owners, production managers and employees of wholesale nurseries was to reduce uncertainty regarding the intended use and goals of AS 2303. This outcome was accomplished by discussion of the project aims and goals with nursery employees, as well as inclusion of nursery employees in field research. One-on-one engagement also helped to fill knowledge gaps among participants regarding the concept of tree stock balance assessment criteria in relation to tree structure, function and performance. We obtained feedback from nursery members in relation to issues with tree quality assessments and expectations from councils and landscapers that purchase nursery grown trees. Overall, through our field visits and coordinated media campaign, one additional outcome of the project was the promotion and use of AS 2303.

Revising tree stock balance criteria in AS 2303 with evidence-based knowledge allows for increased accuracy and improved reliability in tree stock quality testing. If adopted, these changes will increase transparency regarding how tree stock balance criteria are formulated specifically for Australian nursery grown trees. Consequently, the outcomes of this research should aid in alleviating contention or confusion among the growers, specifiers and purchasers of landscape tree stock regarding the intent and use of AS 2303 for testing tree stock quality. In the long term, improvements in tree stock quality testing should result in higher market recognition for growers that produce high quality trees using an accepted national standard. Overall, improved tree stock specifications may aid in the success of broader public initiatives such as the '202020 Vision' by increasing consumer confidence in assessment criteria and promoting the production and supply of high quality tree stock for urban planting and green infrastructure projects.

Additionally, the database broadly encompasses the large variety of native and non-native trees that are produced by tree nurseries for landscape and urban greening projects. As nursery practices evolve in the future, new questions regarding containerized tree growth, morphology and performance may arise. This available dataset may continue to provide insights into tree quality related questions for the foreseeable future. Future ideas and hypotheses regarding morphological tree quality can be tested at multiple levels, including individual species, functional type, site-specific or climate region.

Evaluation and discussion

Across all nurseries, root to shoot balance of 13,820 trees was measured according to AS 2303 assessment criteria (Table 1). *Size Index* and other data were collected for 650 ready to sell batches of containerized tree stock ranging from 18 L to 3000 L (Table 2). This range of container volumes encompasses the entire tree stock balance assessment range in Table E1 of AS 2303. There are 159 tree varieties represented in the database, including 113 unique tree species (Table A2). Of the 650 measured batches of tree stock, 393 were classified as evergreen and 257 were classified as winter deciduous trees. Similarly, 373 batches were native Australian tree species and 277 batches were non-native tree species. This database enables the current project and potentially future research to effectively assess and improve tree quality assessment criteria specific to tree stock commonly produced in Australian wholesale nurseries.

In AS 2303, tree stock balance is assessed by comparing the *Size Index* parameter with the nominal container volume. Specifically, minimum and maximum values of *Size Index* are specified for different container volumes. In this study, only 31% of all measured individual trees were within the specified Size *Index* range (Figure 2). Of the trees that fell outside the specified range, 45% were below the minimum range and 23% were above the maximum range (Table A3). Likewise, following aggregation of measurements to batch-level means of *Size Index,* 62% of the measured batches of tree stock fell outside of their specified range. These measurements indicate that tree stock with standard-conforming morphological quality have a much greater variation in *Size Index* than specified in the current guidelines for tree stock balance. Consequently, this may indicate that the current guidelines are perhaps too general and thus overly restrictive in the context of observed variation in real-world tree production, potentially leading to buyer rejection of suitable tree stock. Alternatively, the observed variation may arise from quantifiable sources, such as species or production differences, that if taken into account may inform refined guidelines. With this extensive database, we quantified to what extent species differences, nursery practices, climate and tree functional type contributed to the observed variation in tree *Size Index* values. Overall, variation attributed to species, nursery site, climate, species origin (native vs. non-native) and tree functional type (evergreen vs. deciduous) combined to explain 43% of observed variation in standardized tree *Size Index* (Table 3).

The variation associated with species differences and nursery site together accounted for nearly two-thirds of the 43% of observed variation in tree *Size Index*. The variation attributable to species differences was most pronounced in trees grown in small to medium sized containers (Figure 2), as evident in observed aggregate differences in size index between evergreen and deciduous species. The variation in *Size Index* attributed to nurseries is also notable as it encompasses the effects of differences in nursery practices across Australia (e.g. irrigation, fertilization or container style). Importantly, the species within nursery variation component, reflecting the fact that not all species were present in every nursery, was equivalent in magnitude to that of the nursery effect (Table 3). This finding is especially crucial when evaluating the utility of AS 2303 as a metric of tree stock balance with a single guideline for all tree stock. The large variation associated with species differences initially suggests that an approach to categorize tree stock into different species groups may be warranted. However, species-specific differences in *Size Index* were also dependent on the nursery in which they were measured, which could arise from differences in batch production history or other factors. As a result, although a large proportion of the variation could be attributed to both species and nursery differences, there is no clear path to create species-specific acceptable ranges of tree *Size Index*.

Overall, *Size Index* values were higher in deciduous trees than evergreen trees. This effect was most pronounced in small to medium sized containers (Figure 3). This simple level of classification helps explain some of the observed variation of *Size Index* values in trees grown in the most commonly utilized container sizes. Measured *Size Index* of large container trees (> 500 L) was generally smaller than the range specified in AS 2303 (Figure 2), largely due to the slowing down of height growth of trees with increasing container size. *Size Index* values for deciduous and evergreen trees in large containers did not differ from each other statistically, but these conclusions are drawn from far fewer measured trees. Non-native tree species also had significantly higher *Size Index* values than native Australian native trees. Tree origin (native vs. non-native) had similar patterns as the tree type (evergreen vs. deciduous) classification as most measured Australian native trees were evergreen, and most deciduous species were non-native. Thus, categorization of tree stock assessment criteria into deciduous and evergreen tree types may serve as a promising way forward to allocate the large inherent variation that is not accounted for in the current single guideline format of AS 2303. Continued data collection on large size trees would be useful to more robustly test if the aboveground size of these different tree types truly converges. We also speculate that growth rate differences could account for higher *Size Index* values in deciduous than evergreen species. For instance, faster height and diameter growth of deciduous than evergreen species could result in a higher *Size Index* values at a given container volume.

Surprisingly, regional climate differences played only a minor role in the amount of measured variation in *Size Index* values. The effect of climate was assessed by both the climate region in which tree stock was grown as well as mean annual temperature and precipitation for each specific nursery site. Neither mean annual precipitation nor mean annual temperature significantly affected measured *Size Index* values, despite large differences in these climatic variables among nursery sites (Table 1). Standardized *Size Index* values were not different among the climate regions (i.e. state/territory) in which measurements were taken (Figure A1) and climate region did not contribute significantly to explained variation in measured values. Climate region did capture a larger proportion of the explained variation than mean climatic variables, but this parameter likely includes variation associated with other factors not relating to growing climate.

Of the components of *Size Index*, the relative variability of tree height and calliper across all container sizes were both quite high (coefficient of variation = 41% and 81%, respectively). For example, height ranged four-fold from 1.0-4.2 m and calliper ten-fold from 11.2-120.0 mm for trees in 45 L containers. The relative magnitude of variation in the two components of *Size Index* has consequences for improving tree stock balance assessment criteria. Reducing the weight of the calliper component in the calculation of *Size Index*, for instance, would reduce the measured variation in *Size Index*, but would not resolve large species-specific differences. Importantly, both tree height and calliper were significantly greater in deciduous trees than evergreen trees and this effect was consistent across all container volumes (Figure 4 A,B). These patterns within the allometric components of *Size Index* lend further supporting evidence to potential categorization of tree stock by tree functional type in order to improve tree stock balance assessment metrics.

Functional differences in tree structure are often used to elucidate observed patterns of aboveground tree allometry. For example, tree stem slenderness is a commonly utilized metric to be indicative of aboveground stability through stem taper, the decline in stem diameter with increased height along the main stem. AS 2303 suggests that nursery grown trees can be separated into simple categories of tall-slender, general or thick stemmed (Appendix D in AS 2303). These categories are suggested to vary depending on climate region or species and likewise determine where individual trees fit in the range of allowable *Size Index* values. In this study, tree slenderness was similar among all climate regions except for South Australia (Figure A2). Skinnier stems in South Australian nursery trees may simply be due to the lack of large container volumes measured, which only ranged from 18-200 L. Additionally, tree slenderness did not differ statistically between evergreen and deciduous trees. These findings are important as the determination of the specified range of *Size Index* values is intended to encompass differences in tree growth rates related to stem form categories (see Table D1 and D2 in AS 2303). Our results suggest that use of tree stem slenderness to determine the acceptable range of *Size Index* has limited utility for Australian grown containerized trees. These findings partially explain how the observed relationships in tree stock balance poorly fit within the assessment guidelines of AS 2303.

Meaningful separation in tree form was detected in parameters related to crown structure between evergreen and deciduous trees. Deciduous trees had a larger crown spread than evergreen trees grown in small to medium sized containers (< 400 L, $P = 0.025$). Evergreen trees had more branches within a given trunk length than deciduous trees across all containers sizes ($P < 0.001$). This indicates that deciduous trees may invest more resources into building a larger spreading canopy and evergreen trees invest into a smaller denser canopy. In addition, the number of branches for a given length of trunk reflects inherent species differences in stem internode length and perhaps growth rate. These functional differences highlight different growth strategies between these two tree types, which coincides with greater measured height and diameter in containerized deciduous trees. The different growth strategies of evergreen and deciduous trees likely account for much of the large variation in *Size Index* values in young trees in smaller containers and provide additional evidence of the validity of assessing the quality of these tree types separately.

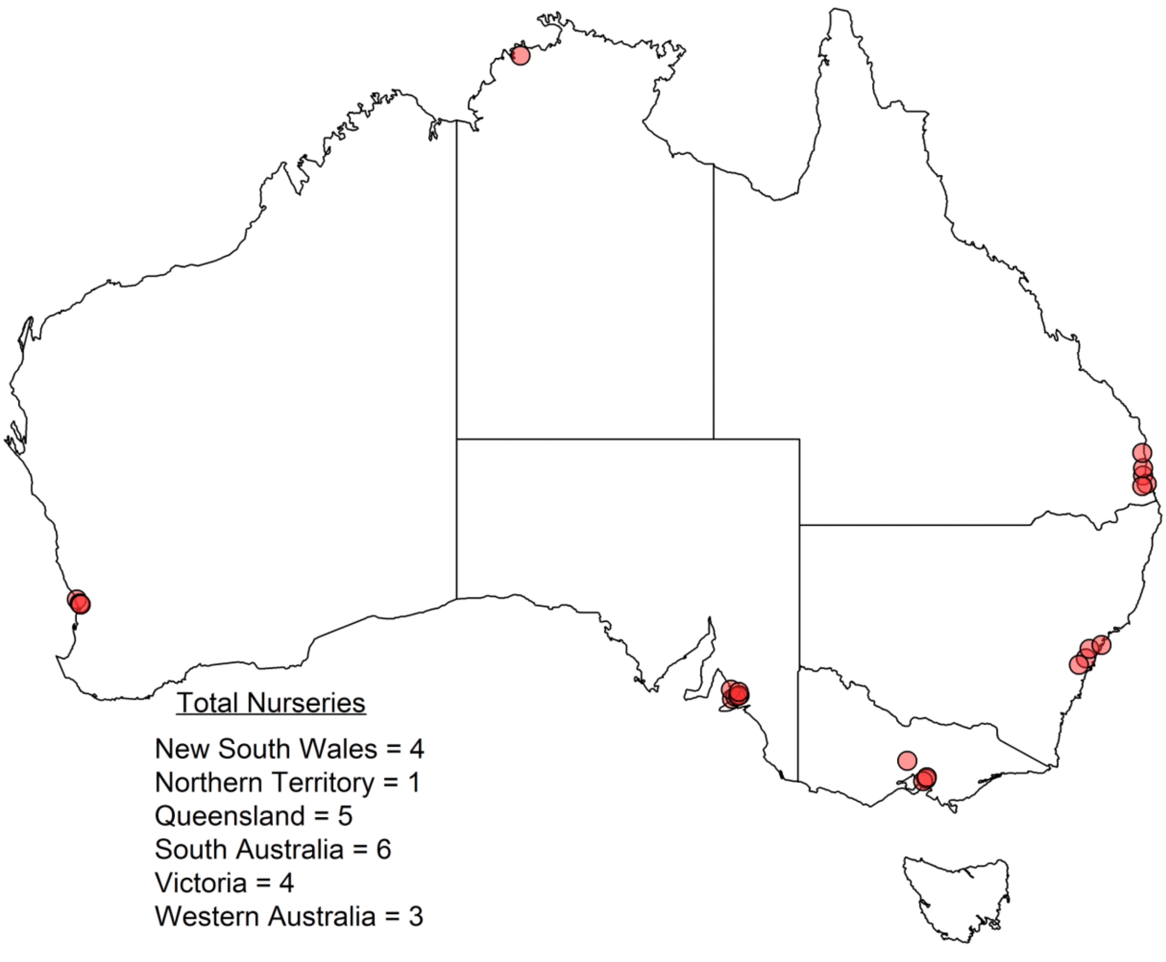

Figure 1. Geographic location of each of the 23 nurseries where containerized trees were sampled. Measurement campaigns were conducted from April 2016 to January 2017.

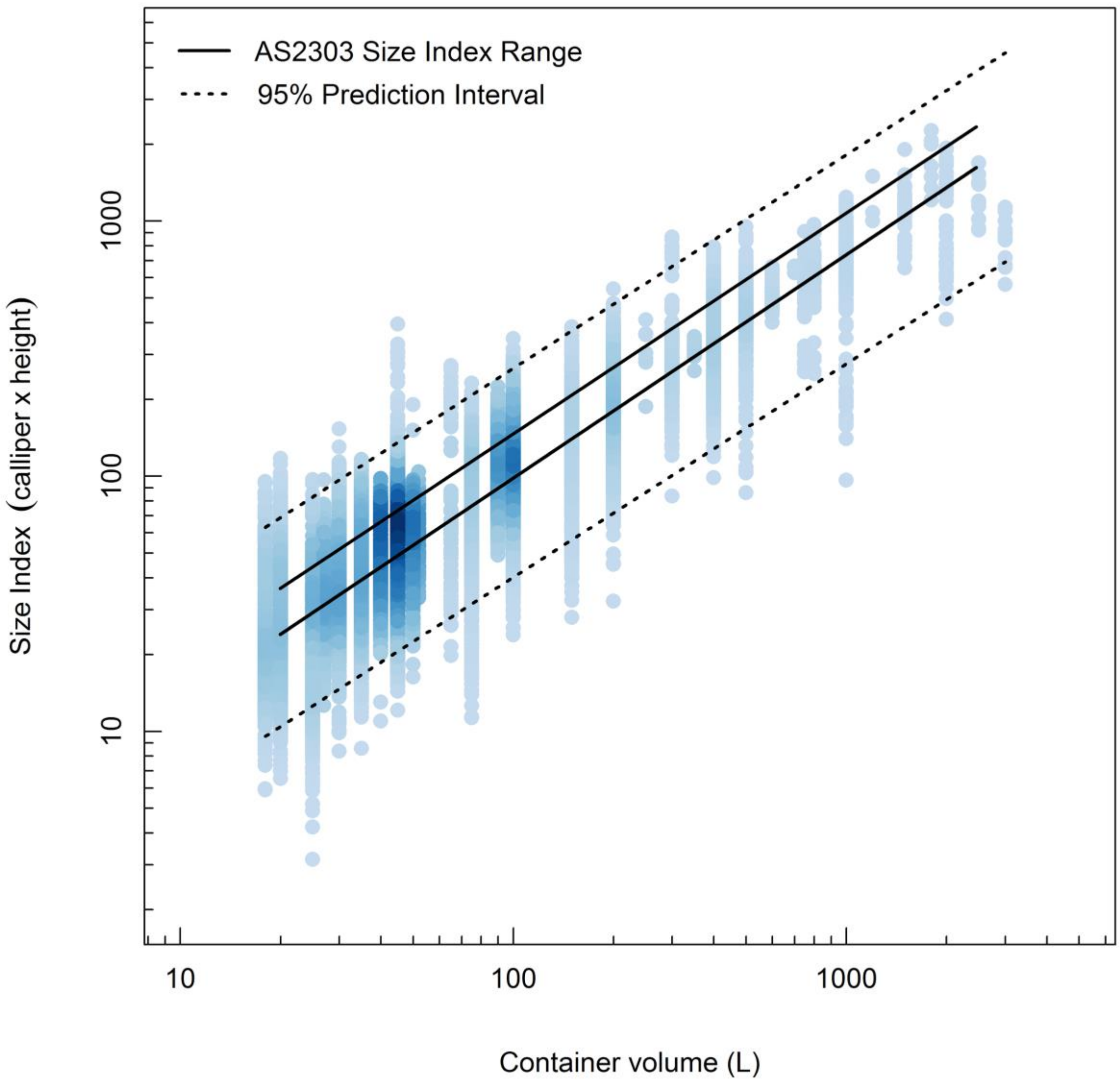

Figure 2. Aboveground *Size Index* in relation to a range of container sizes for trees measured across 23 Australian wholesale nurseries. Circles represent each of the 13,820 trees measured. Colors indicate local density (and overlap) of measurements (darker colours indicate more data). Solid lines represent the minimum and maximum acceptable range as specified in AS 2303. Dotted lines represent the 95% prediction interval based on the measured trees, which effectively include 95% of the data at a given container volume. *Size index* is calculated as calliper (mm) multiplied by tree height (m). Note that the axis scaling is logarithmic.

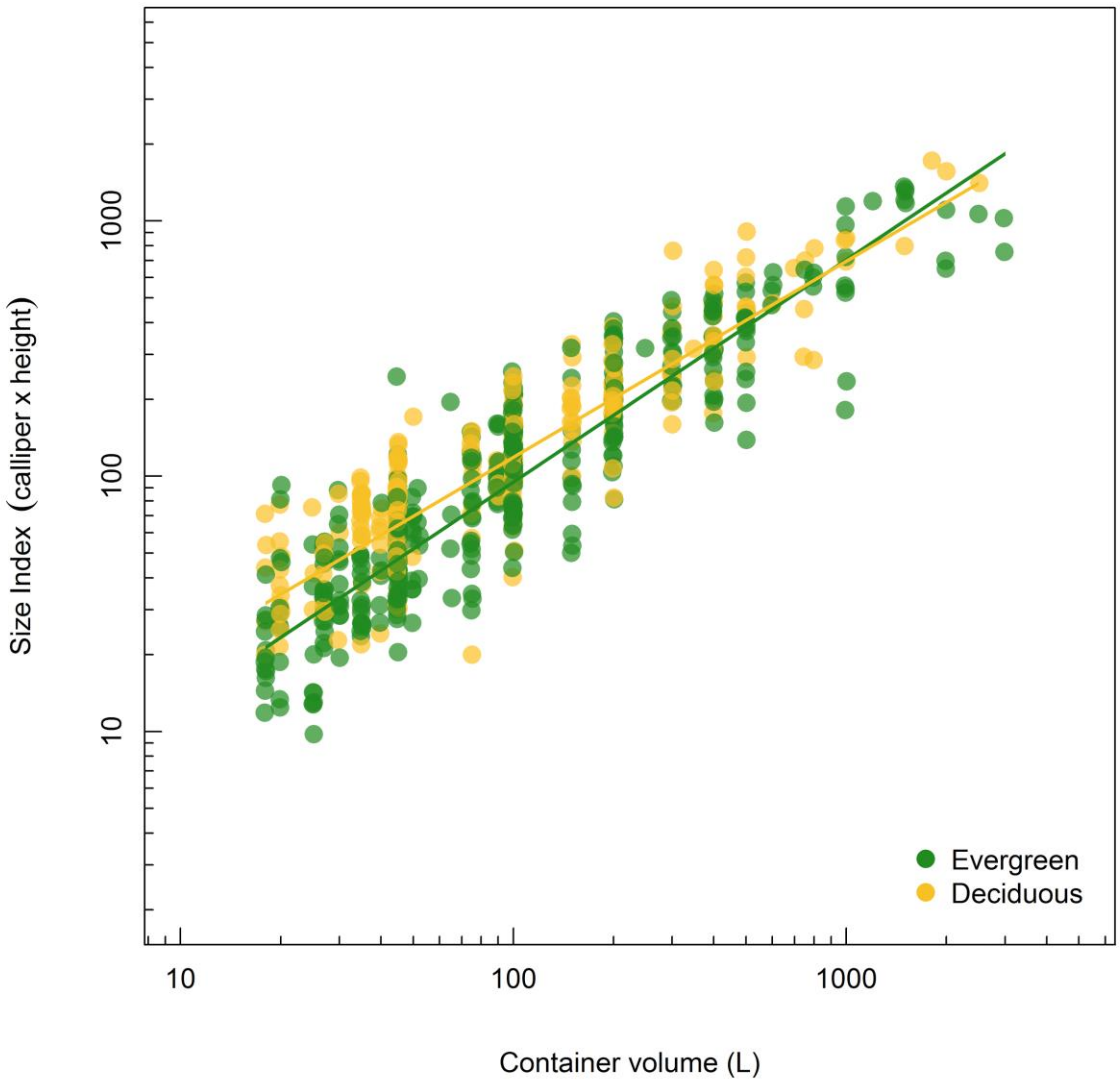

Figure 3. Differences between evergreen and deciduous tree types in measured aboveground *Size Index* across the range of container volumes. In contrast to Figure 2, data were averaged by tree stock batches (n = 650) for all 23 nurseries. Colored lines represent the log linear model fit for each tree type. Deciduous trees had higher *Size Index* values than evergreen trees, particularly over lower range of container sizes.

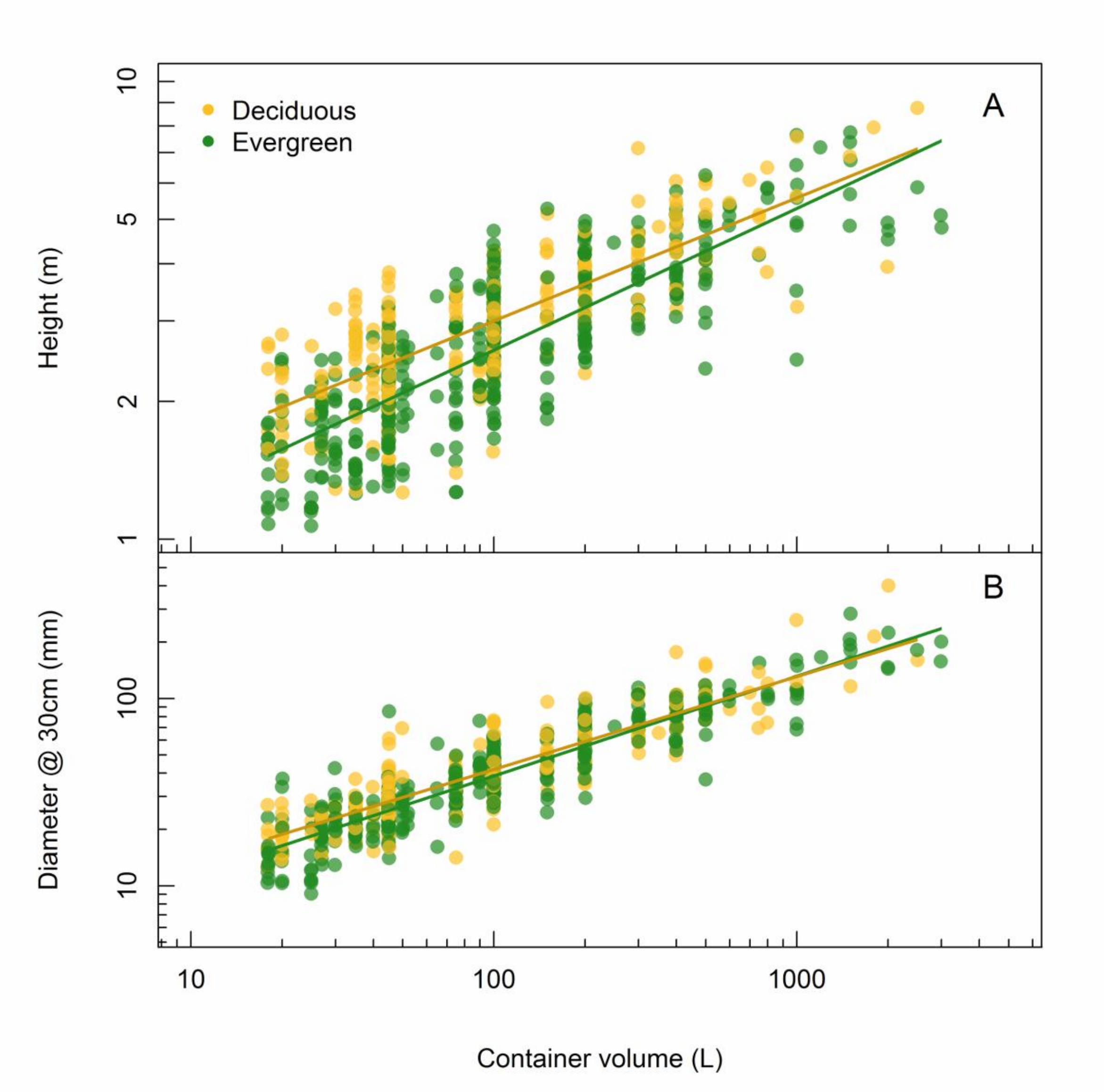

Figure 4. Differences between deciduous and evergreen tree type classifications in the parameters used to calculate *Size Index*. Both height (A) and diameter (B) are greater in deciduous trees than evergreen trees, particularly in small to medium sized containers. As in Figure 3, circles represent tree stock batch means (n = 650) across all 23 nurseries. Colored lines represent the significant log linear model fit for each tree type. Note the high degree of relative variation in both tree height and calliper within individual container volumes.

Table 1. Summary information for each wholesale nursery site. Mean annual temperature (MAT) and precipitation (MAP) represent the 30-year average at each site.

Nursery	Latitude (°)	Longitude (°)	MAT (° C)	MAP (mm)	Trees Measured (#)
Adelaide Advanced Trees	-35.064	138.647	15.4	698	397
Adelaide Tree Farm	-34.995	138.766	14.3	862	89
Alpine Nurseries	-33.659	151.026	16.7	1175	881
Andreasens Green-Kemps Creek	-33.872	150.780	16.8	846	725
Andreasens Green-Mangrove Mountain	-33.327	151.157	16.6	1062	217
Arborwest Tree Farm	-31.726	115.830	18.5	760	764
Benara Nurseries	-31.595	115.724	18.4	747	1180
Cleveland Nursery	-34.942	138.911	13.8	793	197
Darwin Plant Wholesalers	-12.573	131.252	27.3	1408	821
Ellenby Tree Farm	-31.763	115.862	18.3	760	1060
Established Tree Transplanters	-37.812	145.461	13.9	977	409
Fleming's Nurseries	-37.862	145.444	13.4	1085	1209
Freshford Nurseries	-34.823	138.883	14.0	733	864
Greenstock Nurseries	-27.256	153.024	20.2	1283	683
Heynes's Nursery	-34.744	138.609	16.6	456	288
Ibrox Park Nursery	-27.553	153.153	20.1	1192	266
Logans Nursery	-27.000	153.029	20.2	1414	451
Manor Nurseries	-34.970	138.864	13.8	793	140
Mt William Advanced Tree Nursery	-37.239	144.782	12.3	833	1122
Pallara Trees	-27.620	152.998	20.1	1090	329
Plants Direct	-26.476	152.998	20.0	1650	684
Speciality Trees	-37.951	145.340	13.4	1085	886
Trees Impact	-33.180	151.571	17.8	1266	158

Table 2. Summary information for measurement campaigns across each major market region in continental Australia. Tree varieties include all the cultivars measured for an individual species.

Climate Region	Nursery Sites	Tree stock batches measured	Tree varieties measured
New South Wales	4	114	36
Northern Territory	1	36	26
South Australia	6	100	52
Queensland	5	104	41
Western Australia	3	144	47
Victoria	4	152	64

Table 3. Analysis of variance results for the final model of standardized log transformed tree *Size Index*. Model terms in bold are deemed statistically significant ($P \leq 0.05$). The only variables that had a measurable effect on *Size Index* were deciduous/evergreen (Tree Type), and native/non-native (Origin), while no effect of climate was detected. The marginal and conditional R^2 for the full model are 0.16 and 0.43, respectively. The ΔR^2 reflects the reduction in marginal R^2 when that term was removed from the full model. Also shown are the unexplained variances attributed to the random effects terms of species within nursery. The random effects variation between species within a given nursery was similar to variation between nurseries.

Fixed Effects	F	*P*	ΔR^2
Tree Type	46.8	< 0.001	0.09
Origin	15.5	< 0.001	0.14
MAT	0.3	0.59	0.15
MAP	1.4	0.26	0.15
Climate Region	1.4	0.28	0.09
Random Effects	Variance	Std. Dev.	
Species:Nursery	0.002	0.041	
Nursery	0.002	0.049	
Residual	0.008	0.092	

Tree type is evergreen or deciduous; Origin is native or non-native; MAT is mean annual temperature; MAP is mean annual precipitation; Climate region is state or territory.

Recommendations

1. As currently specified in AS 2303, the comparison of aboveground *Size Index* to container volume as the criterion for tree stock balance does not adequately describe existing natural variation in root to shoot balance of otherwise conforming Australian nursery tree stock ready for dispatch. It is recommended that the tree stock balance criteria in AS 2303 be revised.

2. A larger proportion of tree stock (45% of all measured trees), with sound above and belowground morphological quality, were below specified *Size Index* limits than were above (23% of all measured trees). Consequently, one option to better capture the inherent variation in aboveground size would be to lower or drop the minimum range values of *Size Index*. In this case, a greater emphasis and high priority should be placed upon assessing rootball occupancy and the self-supporting nature of the tree stock. This is especially important in the more commonly produced smaller containers sizes, which exhibited a large proportion of stock with *Size Index* values below the specified standard.

3. Specification of appropriate *Size Index* range values for large trees is of particular importance, owing to their comparatively high commercial value. Risk of failure is likely mitigated as a result of well-developed root systems in large container volumes. Given evidence of reduced height growth in large containers, a tailored *Size Index* range for large trees warrants further consideration.

4. In order to ensure that tree stock has not outgrown its container size, it is recommended that a maximum range of *Size Index* values be specified. If the specified range in the current version of AS 2303 is to be revised, the available database could be used to determine the upper range of *Size Index* values to include as a single generalised specification for all species or separation by species type into evergreen and deciduous (e.g. 75% prediction interval).

5. As expected, variation in *Size Index* values attributed to tree species was very large. As species-specific differences were also dependent on the nursery, it is recommended that either a broad categorization (e.g. evergreen or deciduous) or a single generalised specification for all species be used for assessing tree stock balance.

6. Differences in evergreen and deciduous tree stock were widely detected in the height and calliper components used to calculate *Size Index* as well as canopy structural parameters. This suggests that different patterns in growth rates likely occur between these two broad categories in containerized Australian tree stock. This provides a viable alternative to redefine acceptable ranges of *Size Index,* using the available database, according to either an evergreen or deciduous category to better encompass variation across a large range of tree species.

7. Trunk form (i.e. slenderness index) was similar across most climate regions and did not differ among tree type classifications. We recommend eliminating trunk form as a criterion for categorizing tree stock to determine acceptable tree stock balance assessment ranges (see Table D1 and D2 in AS 2303). Trunk form remains useful as a metric to identify outlier tree species with atypical stem structure.

Scientific refereed publications

None to report. Publications are planned for both the literature review and field research components of this project.

Intellectual property/commercialisation

No commercial IP was generated.

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Appendices

Table A1. Summary of all the measured traits during field campaigns. Height and calliper were recorded for all measured trees for each batch of tree stock. All other traits were recorded for a subset of 10 trees (if available) in each batch.

Variable	Units	Description
Height	m	Total length from soil surface to top of tree
Calliper	mm	Trunk diameter at 30 cm from soil surface
Maximum branch length	m	Length of longest branch from trunk
Canopy height	m	Length of canopy from lowest branch to top of tree
Branchiness	#	Number of branches within a 30-cm interval along the trunk

Table A2. Complete list of all tree species measured during field campaigns. Varieties of tree species are included when applicable.

Botanical name	Origin	Tree type	Variety
Acer freemanii	non-native	deciduous	Autumn Blaze
Acer negundo	non-native	deciduous	Sensation
Acer palmatum	non-native	deciduous	
Acer platanoides	non-native	deciduous	Crimson Sentry
Acer rubrum	non-native	deciduous	Fairview Flame, October Glory, Jeffersred
Adansonia gregorii	native	deciduous	
Agathis robusta	native	evergreen	
Agonis flexuosa	native	evergreen	Burgundy
Albizia saman	non-native	deciduous	
Allosyncarpia ternata	native	evergreen	
Angophora costata	native	evergreen	
Araucaria heterophylla	native	evergreen	
Araucaria cunninghamii	native	evergreen	
Banksia integrifolia	native	evergreen	
Barringtonia acutangula	non-native	evergreen	
Bauhinia variegata	non-native	deciduous	
Brachychiton populneus x *acerifolius*	native	deciduous	Jerilderie Red, Bella Pink
Brachychiton rupestris	native	deciduous	
Buchanania arborescens	native	evergreen	
Callistemon viminalis	native	evergreen	Kings Park Special
Callistemon salignus	native	evergreen	
Carallia brachiata	native	evergreen	
Carpinus betulus	non-native	deciduous	Fastigiata
Cercis canadensis	non-native	deciduous	
Corymbia calophylla	native	evergreen	
Corymbia citriodora	native	evergreen	
Corymbia ficifolia	native	evergreen	
Corymbia maculata	native	evergreen	Lowanna
Corymbia tessellaris	native	evergreen	
Cupaniopsis anacardioides	native	evergreen	
Delonix regia	non-native	deciduous	

Botanical name	Origin	Tree type	Variety
Diospyros humilis	native	evergreen	
Elaeocarpus eumundii	native	evergreen	
Elaeocarpus reticulatus	native	evergreen	Prima Donna
Erythrina indica	native	deciduous	
Eucalyptus caesia	native	evergreen	
Eucalyptus erythrocorys	native	evergreen	
Eucalyptus gomphocephala	native	evergreen	
Eucalyptus grandis	native	evergreen	
Eucalyptus leucoxylon	native	evergreen	Euky Dwarf, Megalocarpa, Rosea
Eucalyptus melliodora	native	evergreen	
Eucalyptus nicholii	native	evergreen	
Eucalyptus pilularis	native	evergreen	
Eucalyptus propinqua	native	evergreen	
Eucalyptus resinifera	native	evergreen	
Eucalyptus reticulatus	native	evergreen	
Eucalyptus rudis	native	evergreen	
Eucalyptus saligna	native	evergreen	
Eucalyptus scoparia	native	evergreen	
Eucalyptus sideroxylon	native	evergreen	Rosea
Eucalyptus torquata	native	evergreen	
Eucalyptus tereticornis	native	evergreen	
Eucalyptus victrix	native	evergreen	
Ficus benghalensis	non-native	evergreen	
Ficus benjamina	non-native	evergreen	
Ficus macrophylla	native	evergreen	
Ficus microcarpa	native	evergreen	Hilli, Hilli Flash
Ficus obliqua	native	evergreen	
Ficus rubiginosa	native	evergreen	
Flindersia australis	native	evergreen	
Flindersia schottiana	native	evergreen	
Fraxinus griffithii	non-native	evergreen	
Fraxinus pennsylvanica	non-native	deciduous	Cimmaron, Urbanite
Fraxinus raywoodii	native	deciduous	

Botanical name	Origin	Tree type	Variety
Ganophyllum falcatum	native	evergreen	
Geijera parviflora	native	evergreen	
Ginkgo biloba	non-native	deciduous	
Gleditsia triacanthos	non-native	deciduous	Continental, Elegantissima, Ruby Lace, Shademaster, Sunburst
Glochidion sumatranum	native	evergreen	
Harpullia pendula	native	evergreen	
Hibiscus tiliaceus	native	evergreen	Rubra
Horsfieldia australiana	native	evergreen	
Jacaranda mimosifolia	non-native	deciduous	
Koelreuteria paniculata	non-native	deciduous	
Lagerstroemia fauriei	non-native	deciduous	Fantasy
Lagerstroemia indica	non-native	deciduous	Biloxi, Kiowa, Natchez, Sioux, Tuscorora, Zuni
Liquidambar formosana	non-native	deciduous	
Liquidambar styraciflua	non-native	deciduous	
Lophostemon confertus	native	evergreen	
Lophostemon suaveolens	native	evergreen	
Magnolia grandiflora	non-native	evergreen	Exmouth, Greenback, Little Gem
Malus transitoria	non-native	deciduous	Royal Rain Drops
Melaleuca leucadendra	native	evergreen	Fine Leaf
Melaleuca quinquenervia	native	evergreen	
Melaleuca rhaphiophylla	native	evergreen	
Melia azedarach	native	deciduous	Caroline
Mimusops elengi	non-native	evergreen	
Olea europaea	non-native	evergreen	Manzanillo, Mission, New Norica Mission, Swan Hill, Tolley's Upright
Peltophorum pterocarpum	non-native	deciduous	
Pistacia chinensis	non-native	deciduous	
Platanus x *acerifolia*	non-native	deciduous	
Platanus orientalis	non-native	deciduous	Insularis
Prunus blireana	non-native	deciduous	
Prunus cerasifera	non-native	deciduous	Nigra
Pyrus calleryana	non-native	deciduous	Capital, Chanticleer, Cleveland Select, Winterglow
Pyrus ussuriensis	non-native	deciduous	
Quercus palustris	non-native	deciduous	

Botanical name	Origin	Tree type	Variety
Quercus rubra	non-native	deciduous	
Quercus virginiana	non-native	evergreen	
Randia fitzalanii	native	evergreen	
Syzygium armstrongii	native	evergreen	
Syzygium australe	native	evergreen	Bigred
Syzygium cunninghamiana	native	evergreen	
syzygium tierneyanum	native	evergreen	
Terminalia microcarpa	native	deciduous	
Tipuana tipu	non-native	deciduous	
Tristaniopsis laurina	native	evergreen	Luscious
Ulmus parvifolia	non-native	deciduous	Allee, Athena, Reflection, Todd
Ulmus procera	non-native	deciduous	Vanhoutte
Waterhousea floribunda	native	evergreen	Ameroo, Green Avenue
Xanthostemon chrysanthus	native	evergreen	
Zelkova serrata	non-native	deciduous	GoldenFlame, GreenVase, Musashino, Wireless

Table A3. Percentage of measured trees that fell within, above and below the AS 2303 assessment criteria range for *Size Index* for all container volumes.

Volume (L)	Within range (%)	Over range (%)	Under range (%)	Total trees (#)
18	20	25	55	622
20	31	38	31	792
25	11	9	80	416
27	34	22	44	841
30	25	33	42	663
35	24	22	54	828
40	34	14	52	298
45	34	25	41	3530
50	36	13	51	206
52	37	12	51	94
65	13	35	52	80
75	26	27	47	560
90	38	24	38	340
100	39	24	37	1994
150	31	18	51	403
200	36	19	45	825
250	44	44	12	9
300	31	11	58	226
350	86	0	14	14
400	32	18	50	434
500	43	10	47	243
600	76	0	24	37
700	100	0	0	4
750	35	3	62	37
800	50	8	42	52
1000	22	5	73	158
1200	66	33	00	3
1500	56	3	41	32
1800	43	43	14	7
2000	30	0	70	46
2500	9	0	91	11
3000	0	0	100	15

Table A4. Summary of the 25 most commonly measured tree species during field campaigns. The total number of trees assessed, as well as the number of nurseries and the climate regions (state or territory) for which each species was measured are shown. The range of container volumes shown for each species are available in the full dataset.

Species	Trees Measured	Nurseries	Climate Regions	Container Volumes
Corymbia maculata	680	10	NSW, SA, VIC, WA	18-1500
Angophora costata	651	12	NSW, QLD, SA, VIC, WA	18-600
Magnolia grandiflora Little Gem	432	10	NSW, QLD, SA, VIC, WA	35-1500
Callistemon viminalis Kings Park Special	393	7	NSW, SA, VIC, WA	18-300
Jacaranda mimosifolia	379	12	NSW, NT, QLD, VIC, WA	20-1800
Agonis flexuosa	366	5	SA, WA	18-500
Lagerstroemia indica Natchez	351	9	NSW, QLD, SA, VIC, WA	18-400
Lophostemon confertus	339	9	NSW, QLD, VIC	35-800
Araucaria heterophylla	328	12	NSW, NT, QLD, SA, VIC, WA	30-1500
Waterhousea floribunda	295	9	NSW, QLD, VIC, WA	35-600
Ficus microcarpa Hilli Flash	278	7	NSW, QLD, VIC, WA	30-1500
Banksia integrifolia	276	6	NSW, SA, VIC, WA	30-400
Delonix regia	271	6	NT, QLD, WA	20-300
Lagerstroemia indica Sioux	269	7	NSW, SA, VIC, WA	18-300
Tristaniopsis laurina Luscious	240	7	NSW, QLD, VIC, WA	27-400
Acer rubrum October Glory	227	6	SA, VIC	18-200
Acer freemanii Autumn Blaze	224	5	NSW, SA, VIC	18-150
Eucalyptus leucoxylon Rosea	212	5	SA, VIC, WA	18-100
Eucalyptus sideroxylon Rosea	209	4	NSW, SA, VIC, WA	18-400
Pyrus calleryana Chanticleer	207	5	NSW, VIC, WA	45-800
Melaleuca rhaphiophylla	204	3	WA	35-500
Brachychiton populneus x *acerifolius*	202	7	NSW, QLD, VIC, WA	45-1000
Ulmus parvifolia Todd	202	6	NSW, SA, VIC, WA	27-1500
Platanus x *acerifolia*	185	5	NSW, VIC, WA	45-1000
Eucalyptus leucoxylon Megalocarpa	183	3	SA, VIC	18-100

NSW, New South Wales; NT, Northern Territory; QLD, Queensland; SA, South Australia; VIC, Victoria; WA, Western Australia.

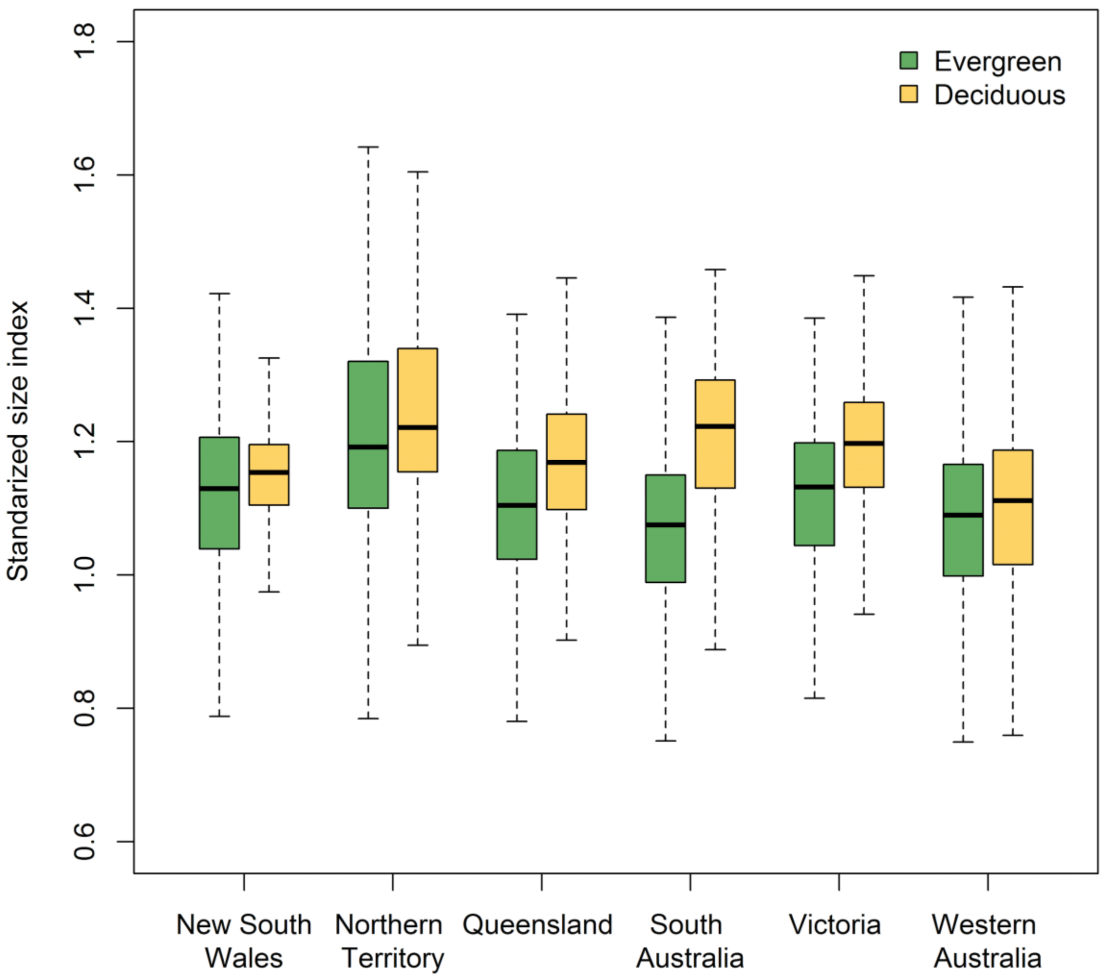

Figure A1. Boxplots of size-standardized *Size Index* values for each climate region. Tree stock are separated into evergreen and deciduous tree types. See methods for explanation of the calculation of size-standardized *Size Index* values.

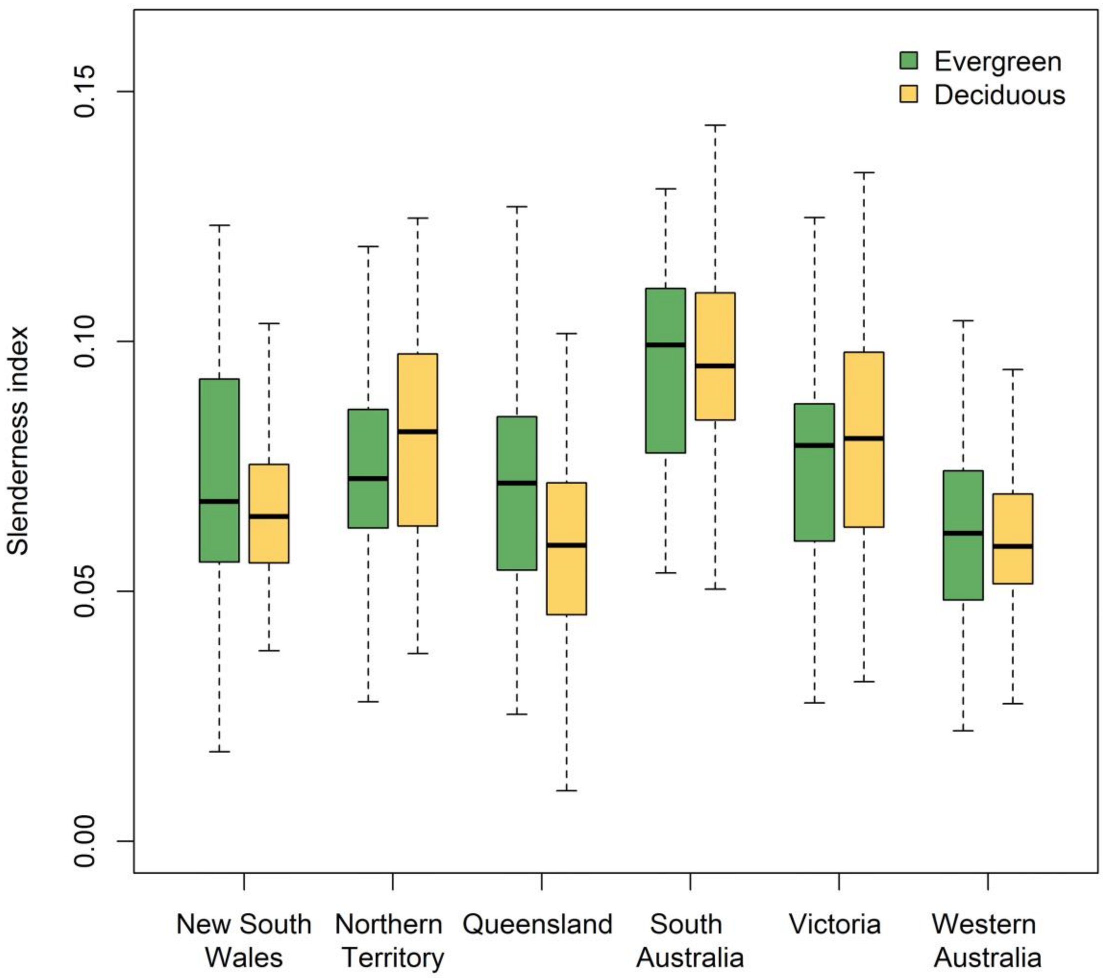

Figure A2. Boxplots of tree slenderness index values for each climate region. Tree stock are separated into evergreen and deciduous tree types.

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

COURTNEY E. CAMPANY, MARK G. TJOELKER, SEBASTIAN PFAUTSCH, REMKO A. DUURSMA, MICHAEL J. ASPINWALL, DAVID THOMPSON

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

Trends in Australian tree nurseries: past and present

In 1997, the Australian federal government set a target to triple the nation's forestry plantation estate by 2020 with the '2020 Vision' initiative (www.plantations2020.com.au). This initiative led a massive decade long expansion of forest plantations (>50 %) in Australia to over 2 million ha, with the majority of the increase composed of a few *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, increased emphasis on quality seedling testing began to ensure containerized seedlings had characteristics that were favorable to out-planting in a wide range of planting sites (Close *et al.*, 2003). Recently, Horticulture Innovation Australia has introduced the new '202020 Vision' that aims to increase urban green space by 20% by the year 2020 (http://202020vision.com.au). This new initiative in the horticulture industry represents a significant market shift towards production of more diverse landscape tree species and introduces a new set of challenges to the Australian tree nursery industry for the foreseeable future.

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

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

Assessing Tree Stock Quality

Evaluating nursery stock quality is necessary to understanding the capacity for growth and survival after out-planting (Wakeley, 1954), yet the quality of tree stock is often assessed too infrequently or only when problems arise (Haase, 2008). Nursery stock quality is the result of a dynamic process that is the culmination of all the practices that have preceded the assessment (Mexal & Landis, 1990). A primary goal of quality assessments is to quantify attributes which accurately assess the condition and potential for growth of different nursery stock types (Wilson & Jacobs, 2006), because nursery stock should embody the structural and physiological traits that can be quantitatively linked to field success (Rose *et al.*, 1990). Many commonly measured traits are now shown to correlate with out-planting performance (Pinto *et al.*, 2015). However, multiple tests of different traits are necessary, as no single characteristic fully encompasses tree stock quality, which is analogous to a physician conducting several measurements to characterize a patient's general health (Ritchie, 1984).

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

Grading tree stock morphology

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

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

The main morphological attributes used to grade nursery tree stock quality are: height, stem diameter and root system size (Thompson, 1985; Mexal & Landis, 1990; Rose *et al.*, 1990; Haase, 2011; Pinto, 2011). The quality of an individual tree represents how each of these main attributes act together and influence one another, such as aboveground sturdiness or the physiological balance between shoots and roots (Wightman, 1999). No single morphological factor has been shown to provide a perfect prediction of out-planting success, but height, stem diameter, root volume and root:shoot are all linked with aspects of potential tree performance (Mattsson, 1997; Haase & Others, 2007). Of these, height and diameter are easily the two most common parameters examined in nursery tree stock, and minimum and maximum targets are usually established in grower specifications (Thompson, 1985; Haase, 2008),including national and international standards for growing containerized nursery stock (see Canadian Nursery Landscape Association, 2006; European Nurserystock Association, 2010; AmericanHort, 2014; Standards Australia Limited, 2015). Assessments used to describe quality nursery stock generally convert these core morphological characteristics into grading standards (Landis & Dumroese, 2006), which aim to keep the size of tree stock in proportion to its container volume.

Aboveground

Metrics of shoot system size reflect how available soil, water, nutrients and competition for light influence tree stock growth and performance (Grossnickle, 2000). For example, height is considered a good estimate of photosynthetic capacity and transpirational area in conifers as it positively correlates to the number of needles on the shoot, suggesting a positive relationship with growth (Haase & Others, 2007). A quality tree should be as tall as possible for a given container volume or rootball diameter, while still possessing an acceptable level of survival potential for the designated site (Thompson, 1985). Larger tree height, however, can have adverse effects on field success in drier sites. This is because taller trees for a given root system size incur greater water loss by transpiration and tend to use more water, despite having greater leaf surface area for photosynthesis (Carlson & Miller, 1990). This has led to height being an inconsistent predictor of out-planting survival for nursery tree stock. Large size class nursery trees are also difficult to lift, handle and plant properly, which can negate advantages of larger nursery tree stock in planting success (Cleary *et al.*, 1978).

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

Belowground

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

In nursery tree stock, the physical volume of roots has been shown to be positively correlated with total mass, diameter, and tree height after out-planting (Rose *et al.*, 1991; Jacobs & Seifert, 2004; Jacobs *et al.*, 2005). The size of the root system, in terms of rooting volume, also likely determines the potential for water uptake prior to new root growth (Carlson, 1986). However, the physical volume of the roots in a given container size could reflect either a fibrous root system or a root system with large tap roots (Haase & Others, 2007). Given the importance of an intact and supportive rootball at planting, it is important for the root system to fully colonize the container and contain actively growing root tips. Seedlings with large numbers of active root tips have more sites for mycorrhizal development and thus increased nutrient uptake and growth in the nursery (Wilcox, 1968; Marx & Barnett, 1974; Mitchell *et al.*, 1984). Thus, assessments of root system quality may be affected by variation in root morphology across species or nursery-specific root management practices.

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

Pitfalls of morphological assessments

Issues with using only morphological assessments, especially single parameter estimates of tree stock quality, have long been recognized to exhibit large variation. Use of simple morphological variables to predict absolute growth often fails to explain large proportions of variation in growth of out-planted trees (Pinto *et al.*, 2011b). For example, Wakeley (1954) first noted how morphological assessments of root collar diameter and height led to unreliable grades of survival and growth in *Pinus palustris* and *Pinus elliottii* seedlings. Measurements of root system morphology are also destructive and time consuming, limiting their application in production nurseries (Jacobs & Seifert, 2004). Although morphological parameters can assess seedling size, growth potential and shoot to root balance; they may not accurately capture seedling physiological quality (Mexal & Landis, 1990; Grossnickle, 2012). Although this issue represents a fundamental problem for the nursery industry, morphological indices still represent the most cost-effective standard practice.

Building quantitative links between morphological parameters

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

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

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

Root to shoot balance in nursery tree stock

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

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

Impact of nursery practices on tree stock balance

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

1. Containerized vs bare root tree stock

Containerized tree stock possess complete root systems oriented downward (McDonald, 1991). Bare root tree stock is grown in open field nurseries, harvested and the soil is removed from the root system (Grossnickle & El-Kassaby, 2015). Containerized seedlings have been generally shown to have greater survival percentage over bare-root seedlings (South *et al.*, 2005), including higher field survival in sites with drought conditions (Grossnickle, 2005 and references therein). This increased survival is attributed to containerized tree stock being easier to plant and having more immediate growth response benefits than bare-root trees (Landis *et al.*, 1990), and likely decreased root desiccation from exposure which is observed in bare root stock (Girard *et al.*, 1997). Although bare root and container stock types have distinct characteristics influencing their field survival, new nursery practices are developing bare-root seedlings with more balanced root to shoot systems (Grossnickle & El-Kassaby, 2015). Current international nursery standards now regulate the size of the bare-root seedling rootball removed in relation to the size of the tree aboveground (see AmericanHort, 2014; The British Standards Institution, 2014). Fundamental differences between these two stock types are important for nursery decision making, as optimal quality specifications need still apply to both (Aphalo & Rikala, 2003).

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

2. Container type

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

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

3. Active root pruning

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

In the absence of any root pruning management, either manually or by container type, root binding and root restriction is likely to occur. Container root restriction can alter root morphology, affecting the ability to absorb water and causing symptoms of water stress in plants, even under well-watered conditions (Krizek *et al.*, 1985). Root:shoot ratios can be confounded in quality assessments by root type. A thick taproot system instead of a large fibrous root system, offers limited surface area for water uptake (Ambebe *et al.*, 2013). Additionally, roots under stress may send inhibitory signals to shoots that inhibit leaf physiology and growth (Passioura, 2002). Active management of root pruning can alleviate these negative feedbacks to physiology, growth and tree balance, which should be prioritized to improve tree stock quality during nursery production.

4. Container volume

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

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

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

5. Irrigation, fertilization and growing media

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

Within nursery environments, maximum shoot growth occurs at high soil water regimes and moderate to high fertility levels (Mexal & Landis, 1990). Increasing the amount of applied fertilization increases the dry weight of both the shoots and the roots (Brissette, 1990), while enhancing the capacity for new root formation (Villar-Salvador *et al.*, 2004a). Fertilization tends to stimulate shoot growth more than root growth by reducing belowground resource limitation (McConnaughay & Bazzaz, 1991; Canham *et al.*, 1996; Villar-Salvador *et al.*, 2004a; Bumgarner *et al.*, 2008; Luis *et al.*, 2009; Jackson *et al.*, 2012). If not properly managed, nutrient deficiencies in nursery trees can also cause negative impacts on leaf physiology, carbohydrate production, height and diameter (Trubat *et al.*, 2010). Alternatively, toxicity and reduced growth can result from over-fertilization of nitrogen and phosphorus in Australian sclerophyll tree species that are naturally associated with low fertility soil (Groves & Keraitis, 1976). Overall, tree balance of nursery tree stock can be significantly altered or specifically managed through fertilization regimes. Fertilization regimes also feedback to out-planting success as alleviation of nitrogen stress may decrease carbon allocated to storage (Green *et al.*, 1994; Holopainen *et al.*, 1995) or nutritional hardening by reduction nitrogen supply may improve field performance in semi-arid or droughted planting sites (Villar-Salvador *et al.*, 2004a; Trubat *et al.*, 2008, 2011).

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

Impact of climate on nursery tree stock

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

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

Using tree balance to mitigate transplant stock

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

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

Future Directions

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

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

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

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GETTING TO THE ROOT OF TREE PLANTING

The success of tree planting starts at the beginning of a tree's life and the eventual impact of nursery production decisions may not be seen immediately. The nursery industry is on a journey to refine a standard for landscape trees, ensuring they thrive for centuries in a greener Australia. This began in April 2015 with the introduction of the Australian standard for tree stock for landscape use (AS 2303:2015). Research is currently underway by the Hawkesbury Institute for the Environment to evaluate this standard and assess the real-world performance of nursery trees grown for landscaping purposes.

Summary

- The standard AS 2303:2015 was formally adopted by Standards Australia in April 2015 following extensive industry consultation.
- Industry called for new research to validate the standard, particularly the root to shoot balance metrics, with a review of the scientific and trade literature and field surveys throughout Australia.
- The list of tree species was identified during meetings of the research committee, made up of selected tree growers, Horticulture Innovation Australia (HIA) and members of Nursery and Garden Industry Australia (NGIA).
- Now halfway through its research cycle, this project is building up a body of data that will eventually contribute to more informed methods and practices to assess the real-world performance of nursery trees grown for landscaping purposes.
- Continued communication to engage growers through the life of the project is planned.


Rootball crown investigation to check for circled roots at surface

THE SIZE INDEX

The current standard, AS 2303:2015, provides a guide for buyers selecting trees to determine if a tree is likely to be good enough to plant out. It gives buyers a way to check for obvious quality problems over different parts of the tree as well as ensuring that the tree's rootball and shoots have the right proportions.

This measure is known as the Size Index, and is like the Body Mass Index that is used to check if a person is in the right weight range.

It is calculated by looking at two parts of the tree:

- The calliper – this is the diameter of the trunk measured at 300mm above the root crown, or 50% of the overall height, measured in millimetres.
- The tree height – this is the height of the tree's above-ground parts from the ground-level/top of the rootball to its highest growing point, measured in metres.

The tree's Size Index is measured by multiplying the tree's height in metres by the calliper:

- Tree height: 2 metres
- Calliper: 50 millimetres
- Size Index: 2 x 50 = 100

A tree with a Size Index of 100 should be in a container with a volume of 70-90 litres when sold, according to the current standard. Expressed another way, a tree in a 70-90 litre container could have a Size Index of 75 up to 137 – so the relationship between container size and Size Index is not exact but more of an allowance to reflect the many root and shoot factors and natural variation in living trees.

Logically, a healthy tree should have a good-sized trunk to support the stem, leaves and branches and these should be in proportion – not too stunted, not too willowy for its species. Likewise, a tree should have an adequately sized rootball to ensure structural support and water and nutrient supply.

But what does this mean in practice and how does this vary by species, climatic region, growing method, pruning or other factors?

Nursery & Garden Industry Australia

This project has been funded by Horticulture Innovation Australia Limited using the Australian Nursery Industry levy and funds from the Australian Government.

Horticulture Innovation Australia

Checking largest branch width at Andreasens Green Kemps Creek NSW

CONTAINER SIZE AND VOLUME

At any given container size, a market-ready tree should have largely filled the container with its roots so that it will not fall apart at planting and leave the roots exposed or loose. It should not be too full, or have roots that have become trapped in a tight circle, or have spent so long in the container that the tree cannot branch its roots outwards into new soil when it is planted.

In practice, this means that the tree's above-ground parts and it's below-ground parts should have grown proportionally and the container size should have been increased by repotting so that the tree has become a 'quality' tree when it is selected for sale.

A STANDARD RELATIONSHIP

The relationship between Size Index and container volume is in the current standard, AS 2303:2015, as a straightforward proportional relationship that says 'the bigger the tree, the bigger the container' with little variation.

TABLE 1: TREE STOCK BALANCE GUIDE DEVELOPED FROM DATA OBTAINED FROM NSW PRODUCTION NURSERIES FOR TREE STOCK IN CONTAINERS

Nominal container volume (L)	Size index range	Nominal container volume (L)	Size index range
20	24–37	150	144–212
25	31–45	160	153–224
30	36–53	200	185–272
35	41–61	230	209–307
40	46–68	240	216–318
45	51–75	250	224–330
50	56–82	285	251–369
55	61–89	300	262–386
60	66–99	350	289–440
65	70–103	400	330–494
70	75–110	500	407–599
75	79–117	600	476–700
85	89–130	750	577–849
90	93–137	1000	739–1087
100	102–150	1200	865–1272
110	111–163	1500	1048–1542
130	128–188	2000	1343–1975
140	136–200	2500	1627–2393

Figure One: the table format data of Size Index ranges as displayed in the Standard AS 2303:2015.

This data is also represented in the following chart and shows a clear proportional relationship with little variation from the trend.

Industry feedback gathered at stakeholder and grower meetings indicated that if a person was selecting trees and using these data as a guide, there would be a strong chance of rejecting otherwise good quality trees. Growers felt that there would be situations where a batch of trees or a particular species rarely or never performed to this trend, as a result of particular seasonal conditions, growth form or other factors.

A lack of information on root to shoot balance at present – particularly as it pertains to varying production regions and species – hampers the integration of these balance metrics into the suite of traits specified in the standard.

While an experienced selector could understand what a tree that is "*healthy, structurally sound, have well-developed roots, have a uniform habit and good balance between the canopy and the rootball*" looks like, there is significant room for interpretation so the standard, particularly the root to shoot balance criterion, does not directly help selectors choose better trees. The root to shoot balance criterion may need some allowance for tree type. It needs to be supported by an evidence-based and simple metric that allows a selector to choose trees efficiently while ensuring they meet quality standards.

Checking tree height at Benara Nurseries in WA

CURRENT STANDARD

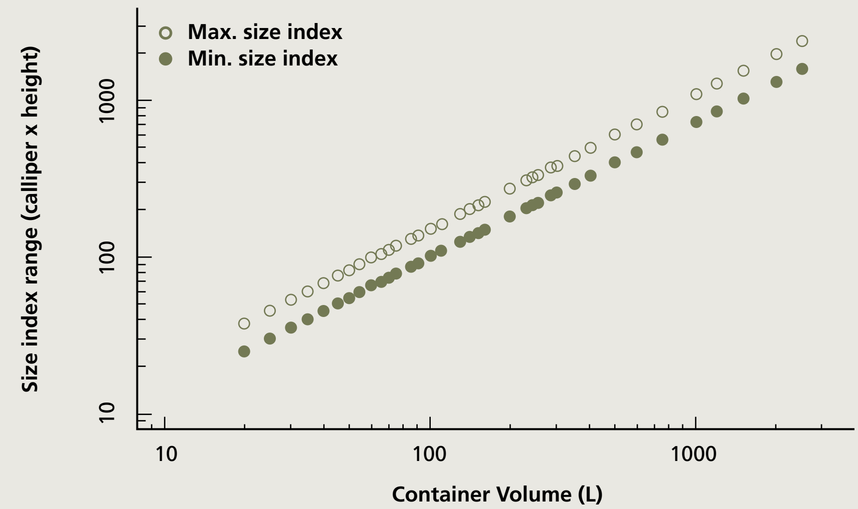


Figure Two: A graphic representation created by the Tree Stock Project researchers of the upper and lower Size Index ranges taken from the Standard AS2303:2015.

OUT AND ABOUT TO OBTAIN TREE STOCK DATA

An initial stakeholder steering committee meeting has been held, and a target list developed identifying 28 tree species and cultivars for assessment across growers and regions.

In 2016, the research team has measured trees in four distinct climate regions of Australia, including New South Wales, Western Australia, the Northern Territory and Victoria. The surveys include a standardised method to collect data from nearly 9700 trees across 117 different tree species/varieties. These measurements have been compared across the entire range of container sizes (20 – 2500 L) specified in AS 2303:2015, as well as with bare-root trees.

Nursery	Region	Trees	Date
Alpine Nursery	Sydney, NSW	919	Apr 26-29
Andreasens (Kemps Creek)	Sydney, NSW	899	May 23-25
Andreasens (Mangrove Mtn.)	Central Coast, NSW	217	May 26
Speciality Trees	Melbourne, VIC	922	Jun 20-22
Mt William Advanced Trees	Melbourne, VIC	1077	June 23-24
Flemings Nursery	Melbourne, VIC	1369	June 27-29
Established Tree Transplanters	Melbourne, VIC	409	June 30-July 1
Darwin Plant Wholesalers	Darwin, NT	821	Aug 8-10
Benara Nurseries	Perth, WA	1208	Sept 12-23
Ellenby Tree Farm	Perth, WA	1081	Sept 12-23
Arborwest Tree Farm	Perth, WA	764	Sept 12-23

Figure Three: Nursery sites visited through September 2016.

THE SAMPLING METHOD

The process to assess a tree is as follows:

1. Measure trunk diameter 300 mm above the root crown (calliper)
2. Measure height of tree using a telescopic height measuring pole
3. Measure the width of the widest branch from the stem outwards to the end of the branch
4. Survey of roots that ranges from basic visual inspection of roots from the root crown to a fully destructive slice sample with the pot removed so that the full rootball can be assessed from the outermost roots to through to the stem.

Dr Court Campany measures calliper at Andreasens Green Kemps Creek

The sampling method also includes visually assessing the above and belowground morphological quality of a representative tree for batches of tree stock that are ready to sell, as specified in Appendix A and B of AS2303.

Researchers evaluate rootball occupancy and root morphology, through either careful removal of a wedge-shaped section of the soil (containers ≤ 45 L) or a top-down inspection of root development of ~150 – 200m into the soil for large containers.

If the representative tree passes both quality assessments, then the size index parameters (height and trunk diameter at 300mm) are measured on a large subset of trees in that batch.

Additional measurements of crown shape and form are collected, as well as leaf thickness for each batch of tree stock.

NEXT STEPS

The next phase of the field trials includes two-week measurement campaigns at six nurseries in South Australia in November 2016.

In early 2017, the team will complete its final interstate visit to Queensland with campaigns at nurseries around Brisbane and Cairns. They will also complete additional site visits within NSW to extend the geographic scope of measurements to include nurseries in Wollongong, Central Coast and Byron Bay.

IMPLICATIONS FOR THE NURSERY INDUSTRY

The aim of this project is to ensure that a drive for tree stock quality across the industry is representative, fair and workable for growers, landscape architects and others selecting and planting trees for Australian landscapes.

This project is building up a body of data that will eventually contribute to more informed methods and practices to assess the real-world performance of nursery trees grown for landscaping purposes. By working alongside growers and others in the industry, the research project can define a more evidence-based standard – one that is trusted and supported as a fair representation of trees being grown in Australia.

This research topic is funded as part of the 'Evaluation of Nursery Tree Stock Balance Parameters' project (NY15001) funded by Horticulture Innovation Australia Limited using the Australian Nursery Industry levy and funds from the Australian Government. Research is being led by the Hawkesbury Institute for the Environment within Western Sydney University. The research team is led by Prof. Mark Tjoelker and includes Dr. Courtney Campany, lead field researcher. The team is supported by David Thompson, Dr. Mike Aspinwall, Dr. Sebastian Pfautsch and Dr. Remko Duursma.

LINKS TO RESOURCES

1. Nursery Papers October 2015 Issue no.9 – Tree Stock Standard AS 2303:2015, Nursery and Garden Industry Australia
2. Standards Australia 2015, AS 2303:2015 Tree stock for landscape use available from *www.standards.org.au*
3. Clark, R. Specifying Trees: A Guide to Assessment of Tree Quality NATSPEC/Construction Information, 2003

IS THE TREE STOCK STANDARD FOR LANDSCAPE USE A VALID TEST OF AUSTRALIAN TREE QUALITY?

Between April 2016 and January 2017, researchers from the Hawkesbury Institute for the Environment at Western Sydney University assessed more than 13,000 trees to see how closely the current standard matches trees of different species and climates in nurseries across Australia.

Background

The Australian Standard for Tree Stock for landscape use AS2303:2015 has 3 sections for quality assessment of containerised trees:

- Above-ground testing
- Below-ground testing
- Evaluation of root to shoot balance

This Horticulture Innovation Australia levy-funded research project has two goals:

1. Conduct a literature review investigating the factors affecting root to shoot balance in containerized trees, and the importance of root to shoot balance for out-planting success.
2. Create an extensive database of measured variables to assess root to shoot balance, via Size Index, in containerized Australian tree stock grown in each major climate region.

Scope of Research

23 WHOLESALE NURSERIES	13,820 TREES MEASURED	18 TO 3000L CONTAINER SIZES
113 TREE SPECIES MEASURED	NATIVE TREE SPECIES	NON-NATIVE TREE SPECIES
EVERGREEN TREE SPECIES	DECIDUOUS TREE SPECIES	

Research Methodology

1. Identify batches of trees ready for sale by consultation with nursery.
2. Complete visual assessments of above and below-ground morphological quality.
3. Measure the tree's height and calliper on a large selection of trees that have passed step 2.
4. Measure additional factors such as canopy width and leaf sizes.
5. Collect climate, production information from each nursery.

Why? *This methodology ensures that the trees being measured possess the quality morphological attributes required at dispatch. From this database we can assess variation in above-ground tree size in relation to container size, species, climate and nursery.*

The Literature Review

Tree quality is the foundation of out-planting success and the capacity for growth following establishment, yet there is no single assessment which can be used to accurately evaluate nursery tree stock quality.

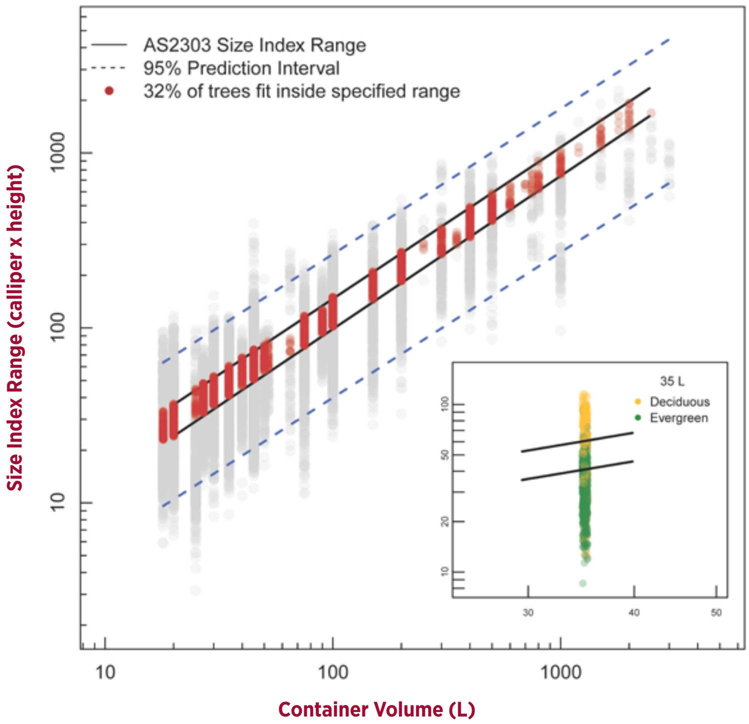
- The 3 most common assessments are height, diameter and root system size.
- Single assessments of nursery quality poorly relate to planting success.
- Evaluating combinations of above and below ground parameters (balance) may better represent tree quality and predict future success.
- However, each of these parameters is influenced by watering, nutrition, climate, species variation and nursery practices.

This makes developing a unified tree balance assessment criteria challenging.

Key Findings

- The specified range of Size Index in AS2303 does not adequately capture the natural variation in 'ready for dispatch' trees in Australian nurseries (Figure 1).
- Small, non-native, deciduous trees in containers less than 50L tended to have greater Size Index values than native evergreen trees.
- Small to medium trees in containers 50 to 500L showed the greatest variability in Size Index which is mostly due to the differences in species.
- Larger trees in containers over 500L typically had a smaller Size Index range than the current standard.
- About one-third of trees measured fit within the current standard's data range across all container sizes of 18 to 3000L.
- 45% of trees measured fall under the acceptable minimum limits of the current standard.
- 23% of trees measured fall over the acceptable maximum limits of the current standard.
- The differences between species was more important than climatic or nursery differences in explaining the variation in Size Index.
- Tree height was much more variable than calliper diameter in the measured trees.

Figure 1. *Above-ground size index across a range of container sizes for trees measured across 23 Australian nurseries*



- Black lines represent the minimum and maximum acceptable range as specified in the existing AS2303.
- Grey circles represent each of the 13,820 trees measured.
- Red circles represent only the trees that fit in the specified range.
- Blue dotted lines indicate where 95% of the measured trees would fit.
- The inset shows the difference between deciduous and evergreen trees in smaller sized containers.
- If only 32% of trees fit into the current standard, there is potential that industry could be rejecting 68% of trees that are otherwise healthy and good quality.

Summary

In summary, the measurements taken across Australia show that landscape trees have a much greater variation in Size Index than the currently adopted standard indicates.

For people selecting trees, this might mean that they are now rejecting trees based on a standard that is too limited for real-world tree production.

The research undertaken has also provided a rare opportunity to develop a rich data set specific to Australian tree stock production nurseries. This data could be used in future research to examine how climate, species and nursery practices contribute to variations in tree stock size and influence tree quality.

A complete report on this research project will be delivered to Industry and Horticulture Innovation Australia by the end of April 2017.

Nursery & Garden Industry Australia

Horticulture Innovation Australia

WESTERN SYDNEY UNIVERSITY

Hawkesbury Institute for the Environment

For more information on the Tree Stock Standards project please visit www.bit.ly/TreeStocks

This project has been funded by Horticulture Innovation Australia Limited using the research and development nursery levy and funds from the Australian Government.

WESTERN SYDNEY UNIVERSITY

Hawkesbury Institute for the Environment

Final Meeting of Steering Committee – Tree Stock Allometry Project

Wednesday 15th February 2017 at 10.00am for 10.30am start

Hawkesbury Institute for the Environment
L9 Conference Room, Building L9
Western Sydney University Hawkesbury Campus
Bourke Street, Richmond NSW 2754

Tea and coffee and lunch will be available at the meeting. Please advise any dietary requirements.

Invitees:

- Dr Anthony Kachenko – Horticulture Innovation Australia
- Prof Mark Tjoelker – Western Sydney University
- Dr Mike Aspinwall – Western Sydney University
- Dr Remko Duursma – Western Sydney University
- Mr David Thompson – Western Sydney University
- Ms Leanne Gillies – Fleming's Nurseries
- Mr Ken Bevan – Alpine Nurseries
- Mr Chris O'Connor – Nursery and Garden Industry
- Ms Carole Fudge – Benara Nurseries
- Mr Hamish Mitchell – Speciality Trees
- Mr Tim Carroll - Andreasens Green

Agenda

10.00am	Arrival, welcome tea and coffee
10.30am	Overview of project: Prof Mark Tjoelker Field trial data and engagement: Dr Court Campany Discussion points: - Implications of the data and findings for the standard - Directions on addressing changes to the standard arising from this research - Communications and outreach on remainder of project - Options for online tool development and usage
12.30pm	Lunch – L9 Foyer
1.00pm	Field site tour to see the extensive experimental tree research facilities at Hawkesbury
2.30pm	Close

WESTERN SYDNEY UNIVERSITY

Hawkesbury Institute for the Environment

Accommodation Options

The Hawkesbury campus is located approximately 60km from the Sydney CBD and about 90 minutes by train from the airport. Therefore it may make sense to stay near to the campus.

We recommend these hotels:

1. Sebel Hotel Hawkesbury – about 15 mins drive from campus in Windsor (4 stars, $179+)
2. Hawkesbury Race club Motel – about 10 mins drive from campus at Clarendon (3 stars, $175+)
3. New Inn Motel – about 5 mins drive from campus at Richmond (3 stars, $150+)

If you are staying overnight, please let David Thompson know and a pickup and dropoff will be arranged.

Transportation to the Hawkesbury Campus

From Sydney Airport:

- Train: Take the Airport Express to Sydney Central and then change to take a train to East Richmond (the line terminates at Richmond but East Richmond is closer to campus). Please see https://goo.gl/AyxARA for the schedule on February 15th to arrive by 10.00am.
- Car: Get on to the M5 and then take the M7 towards Richmond. Take the Richmond/Windsor exit off the M7 and proceed on Richmond Road for about 15km. Drive past the TAFE to Bourke Street. Please visit http://bit.ly/2kRWxCu for the Google maps route.

The Hawkesbury Institute is located in Building R2 and L9. The best entry to the campus is via the College Drive entrance which is off Bourke Street. If you are coming from either the station or by road, it is best to enter via this entry and park in carpark P4. A paid parking permit will be provided.