ASSESSING THE RELATIONSHIP BETWEEN TREE DIMENSIONS IN AN URBAN ENVIRONMENT

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ABSTRACT:

Urban forests can provide vital environmental and social functions if appropriately planned and managed. Tree inventory and tree dimensions are an important part of evaluating and monitoring the growth, size and health condition of urban trees. Accordingly, crown diameter (*cd*), height (*h*) and diameter at breast height (*dbh*) are significant biometric descriptors of tree size and bulk.

When making decisions regarding urban environments it is important to be able to properly estimate these descriptors which are also needed to evaluate for example the so-called zones of upheaval (i.e., areas of interaction between roots and hard surfaces) and soil volume needs for planting trees in urban areas as well as for estimating their growth, control of diseases and preservation requirements.

In line with the above, the scope of this contribution is that of assessing the relationship (via direct field measurements and regression analysis) that exists between the *dbh* of a given tree species relative to its *h* and *cd*. This information can be of assistance when substantiating tree measurements determined via existing mobile mapping technology systems.

One hundred and three mature Norfolk Island pine trees (*Araucaria heterophilla*) located along a tourist shoreline of the Gold Coast (Queensland, Australia) were selected for this work. Their *h*, *cd* and *dbh* were individually measured, processed, and mapped in terms of their coordinate locations (i.e., latitude and longitude). Tree data was captured via field surveys using a diameter tape for *dbh*, and a laser range finder for measuring tree *h* and *cd.* A GNSS enabled digital camera was used to collect pictorial information and location description.

For the case study investigated here, the regression models of *h*=*F*(*dbh*) and *cd*=*F*(*dbh*) reasonably validated (R^2=0.928 and R^2=0.899 respectively) the Australian standard estimates of *h* and *cd* of ornamental trees based on their *dbh*, thus making these estimates easier to determine via simplified mathematical functions. This is because the *dbh* is easier to be measured accurately in the field as compared to *h* and *cd*, and it can also provide information regarding the biomass, volume and carbon storage of trees.

1 INTRODUCTION

The assessment of the economic, social, and environmental benefits of urban forests depends on the accurate quantification of the biometrics of every tree. Yet, till lately, urban forest studies have been based on allometric models developed for trees in plantations and rural forests (Tanka, 2006), despite the diverse growing environments of urban trees.

For street trees especially, this environmental diversity includes (1) more systematic pruning in public parks and streets (2) lower density (3) different nutrient (4) more regular spacing (5) water availability and (6) an array of stressful conditions. In addition, urban forests are valued recreational places for residents, and tree safety is an important subject to address in city planning.

Urban trees are usually kept at a relatively short *h* thus making the precision, accuracy, and usefulness of their measurements a challenging task. This is particularly true in cities where the tendency is to cut or substitute tall trees under utility lines with multi-stemmed and/or short-statured ones, and at time in line with the preferences of residents (Magarik et al., 2020). At any rate, trees in urban areas contribute significantly to human health, environmental quality, and aesthetic.

Hence, researchers have pursued and derived several measuring models that are designed for urban trees involving non-destructive measurement techniques (Monteiro et al. 2016). Modelling of tree growth in urban environments can be used to (1) increase the understanding of tree and urban forest resources (2) develop rural and urban forest policies, development, and administration (3) deliver data to sustain the possible addition of trees within conservational guidelines and (4) regulate how trees influence the environment and therefore improve human wellbeing and environmental quality both in rural and urban areas (Nowak et al., 2013).

Growth and yield of trees are usually modelled by means of stem *dbh* relationships with tree *h* and *cd* (Monteiro et al. 2017). Crown size for instance is an important aspect for tree growth because it governs the amount of solar radiation captured by a tree (Song et al., 2021). Stem *dbh* is also a significant tree dimension and a valuable measurement for predicting the size of a tree.

Dbh has also turned out to be important for models, analysis techniques, and additional statistical tools that allow for the rapid investigation of wide volumes of tree data. In view of this, total *h* and *cd* could be determined as a function of stem *dbh* which in principle is easier to measure in the case of studies related to ground-based forest inventory and complex stand structure determination (Pace et al., 2021).

2 OBJECTIVES

The aim of this research was that of developing a process for defining reliable prediction models of a given tree species in an urban environment. More precisely, the purpose is that of determining the *h* and *cd* as a function of the corresponding *dbh*. The tree species selected in this exercise was the Norfolk Island pine (*Araucaria heterophylla*), a tree species which is often grown as part of ornamental trees located along coastline areas of the Eastern Australia.

The development of prediction models of tree *h* and *cd* from stem *dbh* will allow researchers, arborists, and urban forest managers to model costs and benefits, investigate different supervision conditions, and define the best managerial practices for sustainable tree growing environments (Peper et al., 2001). Importantly, modelling the growth and dimensions of Norfolk Island pines will also assist in their preservation (Miller et al., 2015).

3 MEASURING TREES IN URBAN AREAS

Numerous instruments have been taken into consideration during the past few decades to measure urban trees (i.e., diameter tape, callipers, clinometers, Biltmore stick, Bitterlich's sector fork, the Samoan diameter stick to name some). A comprehensive review of these instruments, describing them in detail including their benefits and disadvantages, can be found in Ibrahim (2014). It is concluded that the diameter tape, callipers, and clinometers offer the best accuracy for the lowest cost and that these instruments do not differ significantly in their accuracy and precision.

Enhanced digital versions of traditional instruments and the advent of novel technologies are starting to substitute some of these instruments. Particularly, remote sensing advances (i.e., satellite imagery and LiDAR) are now more frequently considered for the accurate measurements of the various characteristics of urban trees and forests. However, traditional techniques continue to be the most common methods for urban forest inventories, due to their ease of implementation, effectiveness, accuracy (proximity of the measurement to the real value), reliability, cost and simplicity of implementation.

Instruments are also presently available that incorporate ultrasonic technologies and laser instrumentation with angle measurement for estimating tree heights. For instance, the Vertex (Haglof Sweden AB, Langsele, Sweden) uses ultrasonic sensing and angle measurement to determine *h* or additional vertical linear variables. The TruPulse from Laser Technology is another example of a lightweight laser rangefinder and inclinometer that can be also integrated with an electronic compass. Communication of data is accessible through standard serial ports or via Bluetooth. An advantage of these tools is that *h* is automatically computed, stored and/or displayed to the user.

In urban locations, terrestrial and mobile LiDAR sensors have been considered to assess a diversity of structural tree characteristics, though this has usually been restricted to research purposes (Sackov, 2017). Terrestrial LiDAR data has been used to estimate tree volumes and locations (Bogdanovich et al., 2021). On the other hand, mobile LiDAR scanners have also been adopted for detecting urban trees and compute their *h*, *cd*, and *dbh* with a similar accuracy to field-based measurements (Vandedaele et al., 2022).

Unlike terrestrial and mobile LiDAR acquisition, aerial LiDAR data cannot accurately measure *dbh* due to its aerial perspective (Iizuka et al, 2017). As an alternative, the main applications of aerial LiDAR in urban forestry are to estimate canopy cover, tree *h*, canopy depth, canopy spread and approximate number of trees. Of the three platforms, aerial LiDAR is most likely to be considered for urban forest inventories as it can be implemented over extended areas (Zhang et al., 2015). The detail that it does not estimate *dbh* directly can be averted by using *h* (which can be measured directly) to estimate *dbh* (Weiser et al., 2022). When combined with hyper-spectral imaging, it can also identify specific trees, their associated species, and measure additional biometric features (Clark et al, 2000).

Though LiDAR technology has demonstrated its usefulness for forest assessment, its use for urban forestry inventory is less frequent. In Alonzo et al. (2016) it is suggested that there exist four explanations for this: (1) the complexity of urban areas (2) the spatial diversity of urban forests; (3) the different structure and shape of urban trees and (4) safety reasons (in the case of using drones) as measurements are often carried out in public spaces (i.e., streets and public parks). Moreover, the cost of data acquisition and complexity of processing and analysis have contributed to the cautious uptake of LiDAR-based urban forest inventories.

An alternative to LiDAR is structure-from-motion with multi-view stereo-photogrammetry (SfM-MVS), a technology that integrates stereo-photogrammetry with computer vision. Like LiDAR, SfM-MVS produces spatially truthful three-dimensional models using a selected number of overlapping two-dimensional digital images (Kholil et al., 2021). SfM-MVS has seldom been used in urban forestry outside of research applications (Heo et al., 2019) or in the instance of large and densely vegetated areas.

However, measuring the structure, size and shape of individual trees with SfM-MVS is appealing because of its high accuracy and relatively low Simultaneous Localization and Mapping (SLAM) technology has also been widely considered to measure trees in urban environments. SLAM algorithms combine data from sensors such as cameras and laser scanners to create a map of the environment and determine the location of objects within it.

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This technology has been adopted to create detailed 3D models of trees, measuring their height, diameter at breast height, tree crowns and other attributes. Studies have shown that SLAM can be highly accurate for tree measurement, with errors as low as 2-3% (Perez-Martin et al. 2021). Additionally, SLAM can be used to detect changes in tree health and monitor tree growth over time.

In recent years there has also been a proliferation of apps for mobile phones that use AR (Augmented Reality) incorporating sensors such as clinometers and laser that enable the phone to measure the *dbh* and *h* and estimate tree volumes (www.arboreal.se/en/). By the same token, the integration of the LIDAR scanner into smart phones (i.e., the smart phone iPhone 12 Pro) has made these devices capable of measuring tree dimensions, as well as additional spatial data in the field (Pace et al., 2021)

4 MATERIALS AND METHODS

As already pointed out, the research was conducted in a public park area characterized by a relatively large group of Norfolk

Island pines planted along a shoreline of the Gold Coast in the state of Queensland, Australia. The approximate central coordinates of the study area are 27.9479° S, 153.3982° E. A partial view of the area of interest is given in Figure 1.

The Norfolk Island pine is an evergreen timber and decorative conifer of the family Araucariaceae (Taranto et al., 2022), native to the Norfolk Island, located in the South Pacific Ocean between New Caledonia and New Zealand. The wood of big trees is also utilised in building activities, furniture, and in the building of ships. The tree grows on very sandy soils and is tolerant to sea spray.

Figure 1. The area of interest characterized by a multitude of Norfolk Island pine trees (27.9479°S, 153.3982°E)

Norfolk Island pines are grown as outdoor ornamental trees in areas with a Mediterranean climate. Despite its common name, this tree is not a true pine (Gilman and Watson, 2016). Norfolk Island pines are non-toxic and can remove harmful VOCs (volatile organic compounds) so to make this tree an especially good choice for city park areas or residential properties. It also makes it into the top 50 houseplants that clean the air list by NASA (Wolverton, 1997).

The data capturing for this work followed a random sampling method. After selecting 103 trees arbitrarily within the area of interest, the *dbh* (m), the *cd* (m), and *h* (m) were determined for each tree. For mapping purposes, the tree locations (i.e., Latitude and Longitude) was established by using a GNSS enabled digital camera (Nikon AW130) which also assisted with obtaining a clear image of each sampled tree.

All data required for this study were captured by way of non-destructive measurements. Only one person was involved in measuring the *h*, *dbh*, and *cd* for each tree. The value of *h* was computed from measurements taken with a laser range finder as per the diagram shown in Figure 2.

The laser range finder consisted of a low-cost instrument with an accuracy of +/-0.6 m and +/- 1^0 for distance and vertical angle measurement according to manufacturer specifications (Signify Laser Range Finder EA1440, with slope angle compensation and distance range 3-1000 m). To give an idea of the theoretical standard error to be expected from measuring a 17 m vertical object from approximately 20 meters using the accuracy parameters given above would result in a standard error equal to +/- 0.69 m.

The selection of trees was also based on trees that would visually show relatively small irregular shapes and size, except for abnormally or markedly asymmetrical or leaning trees, but otherwise random samples were considered. The *dbh* was measured with care using a tree diameter tape at 1.4 m (approximately 4.7 feet) from the ground level. The *cd* was estimated by adopting the arithmetic mean of the horizontal *cd* on the north-south axis and on the east-west axis measured by the same laser range finder instrument previously described.

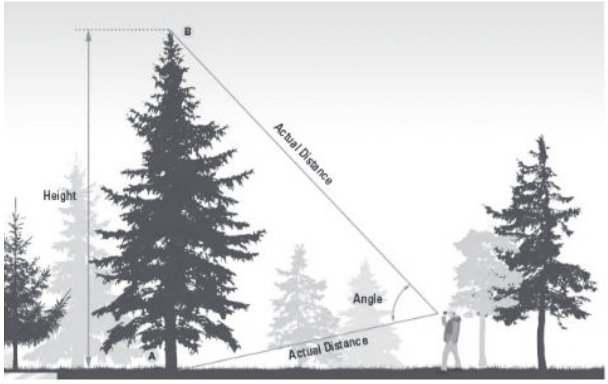

Figure 2. Determination of *h* of a tree using two actual (measured) distances and the angle between them. The *dbh* was measured using a tree diameter tape at 1.4 meters from the base of the tree. Note that depending on the country the *dbh* may be measured at 1.3 m from the base of the tree (Morgenroth et al., 2017)

The law of cosines was selected to determine the *h* of each tree as illustrated in Figure 2 (Bragg, 2008). The Law of cosines states that (Moyer et al., 2017):

$$h^2 = b^2 + c^2 - 2bc*\cos(\alpha) \quad (1)$$

Where b and c are the actual measured distances to the top and bottom of the selected tree respectively, whereas α is the angle between these two distances. If the distances and angles are measured properly, the cosine method is a reliable and an adequate means to remotely estimate tree *h* because it consistently measures a physical entity instead of a projection of the top of the crown. There exist other methods of geometrically determining tree heights using the same instrumentation, examples of these methods relate to the tangent method and the sine method. These are thoroughly described and compared in (Bragg, 2008).

The cosine approach, when applied to the top and bottom of a tree (if these locations are visible at all) should not in principle largely miscalculate tree *h*. It is conceivable for the cosine *h* of a lower part of the crown to be less than the actual *h*, particularly when the real top of the tree is concealed. Therefore, the maximum cosine *h* taken from several distances and angles would provide a more reliable magnitude of the total *h*.

Nonetheless, since there is not a direct way to justify how much (and why) the heights differ from the true value, "true" heights were then needed to weigh against the measured heights. Because it was impracticable to use a tape vertically to measure trees directly from top to bottom, the next best option available to the authors for comparing tree measurements (that is *h* and *cd*) was oblique photography. However, it should be reiterated that the oblique image measurements were only comparative values instead of nominal.

5 OBLIQUE PHOTOGRAPHY

By way of comparing and improving the consistency of the data obtained from measuring the tree *h* and *cd* with the methods described above, a different process was considered to corroborate the dimensions of *h* and *cd*. This was also deemed necessary because the accuracy of measuring *h* and *cd* was not thought to be commensurate with the measurements of the *dbh*. In other words, the accuracy of the tree diameter tape was clearly better than the accuracy of measuring the *h* and *cd* with a laser range finder due to the two instruments differing precisions.

Hence, 35 of the same 103 Norfolk Island pines were re-measured using a technique referred to as oblique photography. Oblique imagery relates to aerial photography that is captured at about 45-degree angle with the ground. The angle that is intrinsic to oblique imagery permits observers to see and measure not just the top of objects, but also the sides. Oblique imagery more closely bears a resemblance to how people usually view their landscape compared to standard orthogonal (straight down or vertical) imagery.

The theory behind this technique is beyond the purpose of this work and the reader is referred to (Kempf et al., 2021) for a detailed explanation of the principles and applications of this technique. Figure 3 is a graphical example of how each of the 35 sampled trees were measured using the oblique image interactive measuring tools of Nearmap©.

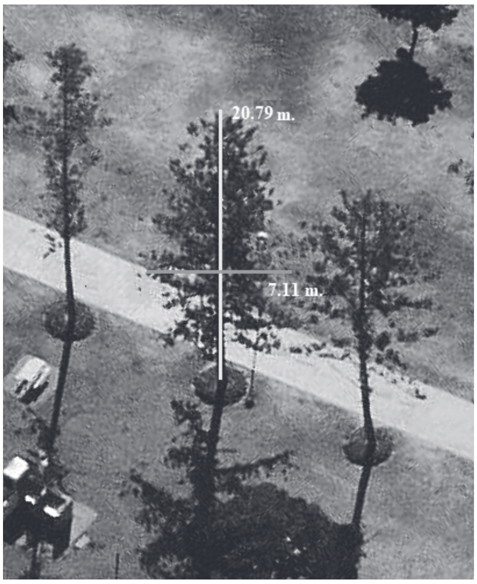

Figure 3. Measuring tree *h* and *cd* using oblique imagery using the oblique image interactive measuring tools of Nearmap©. Only one perspective is shown.

The reason why only 35 of the 103 Norfolk Island pines were sampled relates to the fact that oblique photography requires the object to be measured to be visible in its entirety (if possible, from different views) as it is the case illustrated in Figure 3. The tree *h* and *cd* determined by the laser range finder (observed values) were compared with the *h* and *cd* measured by oblique photography (predicted values) using a basic statistical measure referred to as the RMSE (Root Mean Square Error).

Table 1 shows the RMSE of the differences between the *h* and *cd* values determined from the laser range finder and those obtained from oblique photography. The maximum and minimum difference values of this analysis are also given in Table 1. The results of table 1 offered the authors sufficient confidence that the measurements obtained from the laser range finders were adequate for further data processing and analysis.

Table 1. RMSE (in m) of the differences between the *h* and *cd* of trees measured by the laser range finder and oblique imagery. The figures are based on the analysis of 35 of the103 trees measured with a laser range finder. The maximum and minimum differences are also shown.

6 RESULTS

Dimension	RMSE	Max Diff.	Min. Diff
cd	0.29 m	0.38 m	-0.35 m
h	0.92 m	0.86 m	-1.35 m

Table 2 indicates some statistical figures relevant to the data collected in the field.

Parameters	***h***	***cd***	***dbh***
Min.	6.2	3.1	0.14
Max.	25.2	8.5	0.49
Range	19.1	5.5	0.35
Sum	1125.1	383.9	20.8
Mean	15.8	5.4	0.29
Median	15.4	4.9	0.28
Mode	21.1	6.3	0.37
STDev	1.83	1.55	0.09

Table 2. Statistical summary (m) of the captured data for 103 Norfolk Island pine trees.

The complete datasets provided information for developing regression models between *dbh* and *h* as well as between *dbh* and *cd* for various analytical models, namely exponential, logarithmic, power and polynomials of various degrees. The correlations existing between *dbh* and *h* and *dbh* and *cd* are graphically shown in Figure 4 and Figure 5. The regression models (i.e., linear equations) given in these graphs were determined using Microsoft © Excel Trend and Data Analysis tools.

The linear regression models determined better coefficients of correlation R^2 than the other models considered. It may be mentioned that while polynomials of higher degrees would have to some extent improved the correlation coefficients R^2, it was deemed unnecessary to complicate the models for an improvement only noticeable in the fourth decimal figure of R^2.

Hence, having negligible impact on the outcomes (i.e., results) computed by using equations of Figure 4 and 5. With reference to Figure 4 and 5, a perfect coefficient of determination $R^2 = 1$

was not expected as two trees can have the same *h* but different *dbh* which can be attributed to the shape of the tree and/or other growth variables.

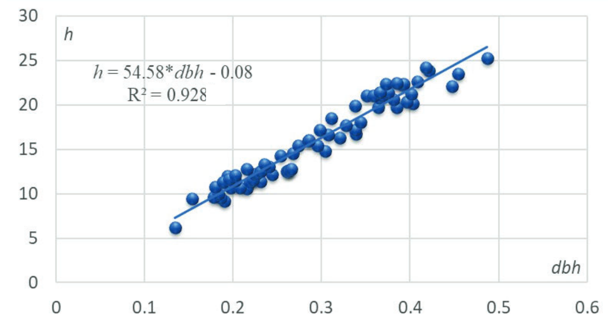

Figure 4. Relationship between *dbh* and *h*. The equation for the linear model and associated R^2 is also shown. All units in the graph are in m.

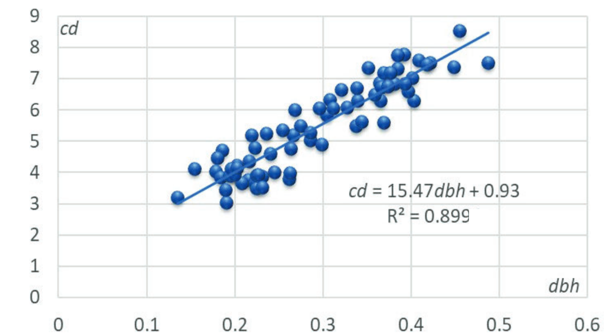

Figure 5. Relationship between *dbh* and *cd*. The equation for the linear model and associated R^2 is also shown. All units in the graph are in m.

6 CONCLUSIONS AND FUTURE WORK

The data captured for tree *dbh*, *h* and *cd* for 103 Norfolk Island pines was analysed. Accordingly, two different linear models were established from the regression analysis where tree *h* and cd were used as dependent variables of their corresponding *dbh*. The relationship between *dbh* and *h* (R2=0.928), the *dbh* and *cd* (R2=0.899) demonstrated a positive and relatively strong correlation. In this contribution, the highest R^2 value was attained by adopting a linear model if compared with other models considered (i.e., exponential, logarithmic, power or higher polynomials).

It can be concluded that there is a likelihood that an increasing *dbh* will reflect in an increasing *h* and *cd* and vice-versa. That is, trees having large *dbh* were taller and with more extended *cd*. In addition, a positive and practical correlation was found between *dbh* and tree *h* as well as between *dbh* and *cd* for Norfolk Pine trees within the area of interest.

In this context, the linear equations determined in this research will offer a method for estimating tree *h* and *cd* with a reasonable level of accuracy. From a realistic viewpoint, it may be inferred from this work that it is relatively uncomplicated to estimate tree *h* and *cd* from *dbh*, being the *dbh* easier to measure especially in ground-based inventory and stand structure biometric studies of trees.

The regression models developed in this contribution were founded on data collected and related to Norfolk Island pine trees grown along shorelines of the Gold Coast, Queensland Australia. The models obtained for this area of interest may be used cautiously outside this location due to tree or plant abilities to modify their architecture so to adapt and cope with changes in its environment especially due to climatic and soil variability.

To complement the current study on trees' biometric, further investigation is necessary to determine tree volumes in parks and their carbon storage above biomass. Urban parks are a valuable natural resource that offers numerous benefits to society, including shade, beauty, recreation, and contributing to climate change mitigation through carbon storage.

After estimating the volume of a tree using the *cd, h* and *dbh*, it becomes possible to determine its biomass and carbon storage. Biomass is the measure of the dry weight of organic material in the tree, which is directly related to the amount of carbon held in a tree's tissues.

This information can guide management decisions such as identifying areas of the park where new trees can be planted to increase carbon storage. Additionally, this information can evaluate the effectiveness of urban parks as carbon sinks and support the development of policies and programs aimed at increasing carbon storage in urban areas.

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