Arboriculture & Urban Forestry 2019. 45(6):239–253

Soil Compaction Affects the Growth and Establishment of Street Trees in Urban Australia

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Abstract. Growing conditions for street tree roots are generally harsh with restricted space and soils compacted from streetscape infrastructure. *Allocasuarina littoralis, Corymbia maculata, Cupressus sempervirens* var. *stricta, Eucalyptus polyanthemos, Lophostemon confertus, Olea europaea*, *Quercus palustris*, and *Waterhousea floribunda* were grown in compacted and uncompacted soils for 20 months in experimental blocks. The bulk density and penetrative resistance of the soils and height, canopy spread, trunk diameter, leaf area, and chlorophyll fluorescence were measured regularly. Root and shoot biomass were determined after harvesting. Since the bulk density of compacted compared to uncompacted soil was root growth limiting, it was hypothesised that species would have reduced growth in compacted soils. However, *C. maculata* and *E. polyanthemos* grew better, *C. sempervirens*, *Q. palustris*, and *W. floribunda* grew well, and *A. littoralis*, *L. confertus*, and *O. europaea* were the worst performing in compacted soil. *E. polyanthemos*, *L. confertus*, and *Q. palustris* had higher canopy:root ratios in compacted soil. *Q. palustris* had greater mass below ground than above, which has implications for its use in confined sites. In a field study, *C. maculata, E. polyanthemos, L. confertus, O. europaea*, and *Q. palustris* growing as street trees were surveyed to determine their rates of establishment and growth under urban conditions. In addition to the soil and tree parameters mentioned above, a Visual Tree Assessment (VTA) was undertaken. *E. polyanthemos* had the largest trunk diameter, height and canopy spread, indicating its potential for rapid establishment in streets. It was the only species with a larger mean leaf area in compacted soil. *E. polyanthemos* and *O. europaea* were the only species classed as healthy from chlorophyll fluorescence but there was no significant difference in fluorescence between compacted and uncompacted soils. VTA showed that *C. maculata* and *O. europaea* performed best and that *E. polyanthemos, L. confertus*, and *Q. palustris* had reduced but acceptable growth in compacted soil. Soils ranged from non-saline to moderately saline and were slightly to strongly acidic. All soils were compacted to some degree and penetrative resistance was at root limiting levels. The results suggest that careful species selection and soil amelioration for species prone to the effects of compaction would facilitate street tree establishment.

Keywords. Australian Street Trees; Soil Compaction; Street Tree Establishment; Street Tree Growth.

INTRODUCTION

Street trees are vital to the urban environment but can be severely site-constrained by urban development (Trowbridge and Bassuk 2004). Urban soils are created by intense human activity and are commonly of poor quality due to chemical and physical constraints with increased bulk density, soil strength, and penetrative resistance usually due to compaction (Craul and Craul 2006; Roberts et al. 2006; Hazelton and Murphy 2011; Fitzgerald 2012). Soil compaction can have a major impact on tree growth and establishment by altering the pore alignment from vertical to parallel to the soil surface (Gregory et al. 2007). Roots either grow through existing soil pores or move particles aside but can only grow through a rigid soil pore with a diameter greater than the root. When roots encounter pores smaller than their diameter and cannot exert enough pressure to expand the pore, they are deflected (Kozlowski 1999).

When a site is relatively undisturbed, local species may prove superior for use in urban landscapes (Smith and Moore 1996), but species from harsher climates often out-perform native species in urban sites (Watson and Himelick 1997). Understanding adaptations to drought, waterlogging, and poor soils can be useful in selecting native trees for urban use where tree establishment can be problematic (Moore 2003; Sæbø et al. 2003; Jutras et al. 2010; Moore 2013). Degraded city soil conditions make it difficult to find different species tolerant of urban conditions (Phillips 2008; Urban 2008) and so a diverse group of species was chosen for this research.

The ideal urban soil for tree growth should mirror an ideal healthy topsoil and be comprised of 45% mineral solids, 5% organic matter solids, and 25% each of air and water (Trowbridge and Bassuk 2004). Such a soil allows for root penetration and deep rooting due to a high level of aggregation and a high proportion of macropores that allow water percolation through the soil and entry of air as the water drains. A soil with good structure can be damaged if the macropore pattern is altered by disturbance of the aggregates, and even in well-aggregated soils with increasing depth, the volume of large pores and available oxygen typically decrease (Perry and Hennen 1989; Acquaah 1999; Watson 2006). While bulk density can be decreased with organic matter, which increases aggregation and promotes structure, it generally increases with soil depth due to reduced organic matter and associated microorganisms and the weight of the soil above (Urban 2008). Total porosity can be as low as 30% in heavily trafficked compacted soils and as high as 95% in some peats (Handreck and Black 1999).

Soils compact due to compressive and vibrational forces, which degrade soil structure by crushing macropores and filling pore spaces as soil particles become densely packed after the mechanical force exceeds the shear strength of the soil (Trowbridge and Bassuk 2004). Compaction increases soil density and strength by increasing the forces holding the soil together. It prevents soil settling, complicates diffusion pathways, slows infiltration rates, and slows the soil's ability to drain quickly, reducing the level of air in the soil (Watson and Kelsey 2006; Bühler et al. 2007; Sinnett et al. 2008). Compaction usually occurs in the upper 15 cm, directly affecting the root zone, and can vary over short distances and with depth (Pittenger and Stamen 1990). The reduction in macropores, decreased soil aeration, and altered soil water status can create an anaerobic rhizosphere leading to root and tree death (Smith and Moore 1996; Acquaah 1999; Roberts et al. 2006; Hascher and Wells 2007). If the diffusion rate is low, roots may be confined to the soil surface (Urban 2008), and root elongation, root and shoot dry weights, and leaf area can be affected by high levels of compaction (Tubeileh et al. 2003; Bühler et al. 2007). Vertical and horizontal root growth can be hindered, resulting in small, shallow root systems.

When roots encounter compacted soil, they generally grow parallel to or away from the compacted zone, but growth may slow or stop (Perry and Hennen 1989; Trowbridge and Bassuk 2004). If lateral roots can fit through the pores of compacted soil, then growth continues while the main axis of the root is constrained (Coder 1998), resulting in increased branching and radial thickening of roots, which can exert greater force and penetrate further into compacted soil (Coder 1998; Gregory 2006; Day et al. 2010). Trees growing in compacted soil tend to have spreading root systems often less than 10 cm deep (Smith and Moore 1996). Species with high root:shoot ratios have a greater ability to penetrate compacted soil (Watson and Himelick 1997; Sæbø et al. 2003; Jutras et al. 2010).

Heavy machinery can compact soil by the load of the wheels exerting a vertical force, wheel slippage causing shear stress, and the force of the engine vibrating through the tires (Smith and May 1996; Watson 2006; Hascher and Wells 2007). The use of such machinery should be avoided in wet soils, and care must be taken to avoid compacting street tree planting sites (Rolf 1991). Compaction is the most common form of soil damage and is difficult to ameliorate, as only part of the soil deformation can be reversed (Kozlowski 1999). Rectifying compaction, especially on construction sites, is difficult, as it can require cultivation to the depth of the subsoil which machinery usually cannot reach (Roberts et al. 2006; Gregory et al. 2007). Preventing compaction is the best strategy, as it is more effective and less costly than alleviating it (Handreck and Black 1999; Kozlowski 1999; Urban 2008).

This paper reports an experiment and survey aimed at determining whether there were differences in the growth and establishment of trees grown in compacted and uncompacted soils. The experiment investigated whether there were differences in canopy and root growth, differences between the north/south and east/west canopy and root dimensions, and differences in root length or depth within and between species growing in compacted or uncompacted soils. The survey aimed to examine the health, growth, and the soil conditions under which street trees planted 24 to 36 months earlier were growing. Both the experiment and survey collected data on tree size and condition, leaf area and chlorophyll fluorescence, and soil bulk density and penetrative resistance.

MATERIALS AND METHODS

Experiment

Eight species commonly planted in suburban Melbourne were selected from a study of street trees in suburban Melbourne (Beer et al. 2001):

- *Allocasuarina littoralis* (Salisb.) L.A.S. Johnson, (Black Sheoak)
- *Corymbia maculata* (Hook.) K.D. Hill and L.A.S. Johnson (Spotted Gum)
- *Cupressus sempervirens* L. var. stricta (Ait.) (Mediterranean cypress)
- *Eucalyptus polyanthemos* Schauer (Red Box)
- *Lophostemon confertus* (R. Br.) P.G. Wilson and Waterhouse (Brushbox)
- *Olea europaea* L. (European Olive 'Tolley's Upright')
- *Quercus palustris* Muenchh (Pin Oak)
- *Waterhousea floribunda* (F. Muell.) B. Hyland (Weeping Lilly Pilly)

They were grown in the research station at the University of Melbourne, Burnley College, 500 Yarra Blvd, Richmond, Australia. The soil of the research station is classified as a fine sandy loam. Plants were in 15-cm pots, except for *O. europaea* which were purchased in 20-cm pots, and *Q. palustris* were bare rooted.

The block design comprised eight species, two treatment factors (compacted or uncompacted soil), and eight replicates, with each block containing all eight species, giving a total of 128 plants. Each block measured 12 × 5 m with trees planted at 1.5 m centers. The compacted and uncompacted blocks were randomly allocated along with the location of each species within each block. The blocks were prepared by removing turf, ripping the soil using a tractor and single ripping blade to a depth of 80 cm with 40 cm between rip lines. The compacted blocks were compacted with a Dynapac CC900G ride-on vibrating roller. The target levels of compaction were greater than 2.5 MPa, and blocks were compacted one at a time, with four passes of the compactor. Bulk density was measured in all blocks using the volume excavation technique, in which a sample of soil is excavated and the hole filled with sand (or water) to determine its volume. The sample is dried and weighed and the dry weight of the soil sample is divided by the volume of the hole to determine bulk density (Craul 1992; Lichter and Costello 1994).

Trees were 30 to 40 cm tall at the time of planting, and their heights were recorded and trunk diameter measured at 20 cm above the soil using a NSK Electronic Digital Calliper. A small paint mark was used to position future trunk diameter measurements. Planting holes were dug in the uncompacted soil with a hand spade, but in compacted soil a mattock was used. Every two months, trunk diameter, canopy spread on the north/south and east/west orientations, and height (ground level to the tallest branch tip) were measured. For trees with multiple leaders or epicormic shoots, the original leader was measured, except where it had died; then the tallest shoot was measured.

A 7.5-cm thick layer of mixed-particle size, organic mulch was applied to both soil treatments to suppress weed growth, reduce evaporation from the soil, and add organic matter. The mulch was maintained at a thickness of 7.5 cm. Over the 20 month growth period, the trees were checked two to three times per week to assess any damage, irrigation requirements, stake maintenance or removal, mulch level, weeding requirements, or occurrence of pest attack.

In Australia, most street trees are not irrigated automatically, but many are hand-watered over the first few summers, so each plant was hand-watered with a hose until the water pooled on the surface, then watered a second time until the water pooled. Weeds were sprayed with Roundup (glyphosate 360 g/L, Monsanto Australia). Because of insect attack, *C. maculata, E. polyanthemos*, and *W. floribunda* were sprayed twice with Yates Pest Oil (839 g/L petroleum oil) at a rate of 25 mL/L. *C. maculata* was also treated once with Confidor (imidacloprid, at a rate of 1 g/L) for caterpillar infestations. Three *C. sempervirens* trees showed symptoms of cypress canker (*Seridium* species), and for two the affected foliage was removed, but a third was so badly affected that it was replaced. Sufficient trees were available for replacements, so with few mortalities and eight replicates there was no impact on statistical analyses.

A portable Hansatech Plant Efficiency Analyser (PEA) was used to measure chlorophyll fluorescence (Fv/Fm) on the leaves of the trees except for *A. littoralis* and *C. sempervirens*, as their foliage was too fine for testing. Fv/Fm data are indicative of photosynthetic efficiency, and when environmental stress impacts upon photosystem ll of tree leaves, there is a decrease in the value of Fv/Fm. The method used was to the manufacturer's specifications, and four readings per tree were taken using leaves from north, south, east, and west facing sections of the canopy in the late morning and in the early afternoon over several days due to the large number of plants. Leaf area was measured, except for *A. littoralis* and *C. sempervirens,* with a LiCor Biosciences LI 3100C area meter.

Two leaves each from the north, south, east, and west facing direction were scanned.

Soil bulk density was measured at the completion of the experiment using a Dormer split core soil corer with a 40-cm long sampling tube. Once the tube was 35 to 40 cm deep, it was removed, providing an undisturbed core sample 4.8 cm in diameter. The cores were divided into three sections (0 to 10 cm, 10 to 20 cm, and 20 to 30 cm), and three samples were taken per block from randomly selected locations (3 samples per block, 3 depths, 16 blocks, 144 samples). The samples were placed in a Labec oven at 80° C for 24 hours, weighed, and the bulk density calculated by dividing dry weight by volume. A Rimik CP10a Cone penetrometer was used to determine soil compaction. The probe was inserted into the soil approximately 30 cm from each location of the final bulk density tests. Three measurements were made in each block to a depth of 20 cm (48 samples).

At final harvest, 20 months after planting, trees were cut at ground level and bagged. The bags were placed in an oven at 80° C and weighed one week later, then periodically until the weight stabilized. Because of the large volume of material, it took several months to complete drying. Roots were excavated from the blocks using an air compressor (130cfm) with a 1.9-cm diameter air hose and Kennard nozzle (3.0-cm diameter flattened to a 0.5-cm width) from which the air was expelled. Starting from the trunk, the soil was blown from the roots, exposing the root system. A 1.5t mini excavator was used to move the excess soil from the root system. North was marked on the trunk using a paint pen so that when the roots were lifted from the ground, orientation was preserved. While the roots were still in the ground, the length of the longest root growing to the north, south, east, and west was measured for each tree. Each root system was cut up and the dry weight determined using the same method as for the trunks and foliage.

Survey

Five of the species from the previous experiment were surveyed growing as street trees within the suburban City of Hume (20 km from the centre of Melbourne), which manages approximately 80,000 street trees. Approximately 10 to 12% of street trees die within three years of planting, mainly due to vandalism. Fifteen *C. maculata, L. confertus, Q. palustris,* and 16 *E. polyanthemos* planted for 24 months, and 15 *O. europaea* 'Tolley's Upright' planted for 36 months were surveyed. The trees were irrigated (20 and 40 L) every seven days in the first year and every 21 days for the second and third year after planting.

For each species, three trees from five different streets were chosen by Stratified Random Selection. If the street was long, it was divided into sections, and trees were selected from each section and from both sides of the street, making sure they were not clustered, to give generalized data and a good representation of the tree growth and growing conditions along the street.

Visual Tree Assessment (VTA) was undertaken using headings modified from Lonsdale (2001), including general information, tree characteristics, site conditions and usage, tree condition, and remedial works to improve tree health and reduce hazards (Fitzgerald 2003). The Tree Condition category was an assessment of the tree's general condition and was divided into four sections: Roots, Trunk, Branches, and Foliage. Each field had a 1 to 5 rating score, with 1 having major problems and 5 having no problems. There were 20 category fields in total, which provided a perfect score of 100 points; the healthier the tree, the higher the score (Table 1).

Bulk density was measured at two locations for each tree just outside the mulched area, 1 m from the trunk and parallel to the road. This was done to obtain accurate bulk density data, as the soil profile under the mulch had been disturbed during planting. The core sampling technique (Cass et al. 1998) was used to obtain core soil samples, which were oven dried at 80° C for 24 hours and then weighed. Samples were collected using a slide hammer constructed at the university that was similar to an Eijkelkamp, core cutter model RAW 2010/6, 08.09. A Rimik CP10a cone penetrometer was used to measure soil compaction. The readings were taken at a depth of 20 cm, and four readings were taken per site. Two of the readings were adjacent to the location of the soil samples for bulk density, and readings were taken 1 m from the tree trunk.

The chlorophyll fluorescence of the foliage was measured as an indicator of the stress levels of the plant in the late morning and in the early afternoon. Individual leaf area was measured for each tree using the same leaves as measured for fluorescence and same method as in the experiment. Data were analyzed using Minitab 16 and the ANOVA General Linear Model (GLM). The separation of each pair of means was done using LSD with significance at $P < 0.05$.

Table 1. Tree condition assessment of roots, trunk, branches, and foliage and their component categories.

Tree part	Rating categories	Score range	Tree part	Rating categories	Score range
Roots	Anchorage	1-5	**Branches**	Attachment	1-5
	Exposed roots	1-5		Epicormic shoots	1-5
	Girdling roots	1-5		Deadwood/dieback	1-5
	Pest or disease	1-5		Low branching	1-5
	Root score range	**4-20**		Pest or disease	1-5
Trunk	Physical damage/injury	1-5		Crossing/rubbing branches	1-5
	Multiple stems	1-5		Broken branches	1-5
	Trunk taper			Annual shoot tip growth	1-5
	Lignotuberous /epicormic shoots	1-5		Even branch distribution in canopy	1-5
	Pest or disease	1-5		**Branch score range**	**9-45**
	Trunk score range	**5-25**	**Foliage**	Leaf size and colour	1-5
				Pest or disease	1-5
				Foliage score range	**2-10**

Rating descriptor	**Major problems**	**Significant problems**	**Some/few problems**	**Minor problems**	**No problems**
Rating value	**1**	**2**	**3**	**4**	**5**

Minimum total rating score 18 **Maximum total rating score 100**

RESULTS

Experiment

The mean bulk densities for the uncompacted blocks for initial and final tests were 1.50 Mg/m^{-3}, and for the compacted blocks the initial test was 1.88 Mg/m^{-3}, and the final test was 1.60 Mg/m^{-3} (Table 2). ANOVAs showed a significant difference between the uncompacted and compacted sites ($P < 0.05$) which was maintained for the duration of the experiment. Soil penetrometer readings were significantly higher in compacted (mean 2.95, range 2.30 to 3.80 MPa) than uncompacted (mean 2.09, range 1.30 to 2.70 MPa) soil ($P = 0.012$).

At the completion of the experiment, the bulk densities at the three sample depths for compacted soil were all higher than for the uncompacted soil, but only significantly so for the top level. There was also a significant difference between the depths for uncompacted soil with a difference of 0.04 Mg/m^{-3} between the top and the middle samples (Table 3).

Separate ANOVAs showed that *L. confertus* ($P = 0.023$) and *O. europaea* ($P = 0.038$) had significantly larger trunk diameters in uncompacted soil (Figure 1), that *E. polyanthemos* ($P = 0.037$) was significantly taller in compacted soil (Figure 2), and that *L. confertus* and *O. europaea* had wider north/south canopy widths ($P = 0.031$ and $P = 0.016$, respectively) and east/west ($P = 0.016$ and $P = 0.009$, respectively) in uncompacted soil.

Figure 3 shows that the mean full canopy widths were greater for uncompacted than compacted soils.

Table 2. Initial and final bulk density means for compacted and uncompacted soils. When comparing the same level of compaction, LSD = 0.08. Bulk density means in the same row or column with a different letter are significantly different ($P < 0.05$).

Bulk density	Bulk density compacted Mg/m^{-3}	Bulk density uncompacted Mg/m^{-3}	LSD	*P*-value	Penetrative resistance compacted MPa	Penetrative resistance uncompacted MPa
Initial	1.88a	1.50b	0.13	< 0.001	> 2.60	< 1.00
Final	1.60c	1.50b	0.08	0.011	2.95	2.09
Treatment mean	1.70ac	1.50b	0.09	< 0.001		

Table 3. Mean final bulk density at different soil depths for compacted and uncompacted soils. Means in the same row or column with a different letter are significantly different (*P* < 0.05).

Depth	Uncompacted Mg/m^{-3}	Compacted Mg/m^{-3}
Top (0-10 cm)	1.50a	1.60bc
Middle (10-20 cm)	1.54b	1.58
Bottom (20-30 cm)	1.55c	1.57

There were two significant treatment effects for root length: species ($P < 0.001$) and compass bearing ($P = 0.033$). It was expected that the root length for species would be different, but north growing roots were significantly longer than those from the east (Table 4).

The ANOVA for root length showed that there were significant species differences ($P < 0.001$). Roots of *O. europaea* were significantly longer in

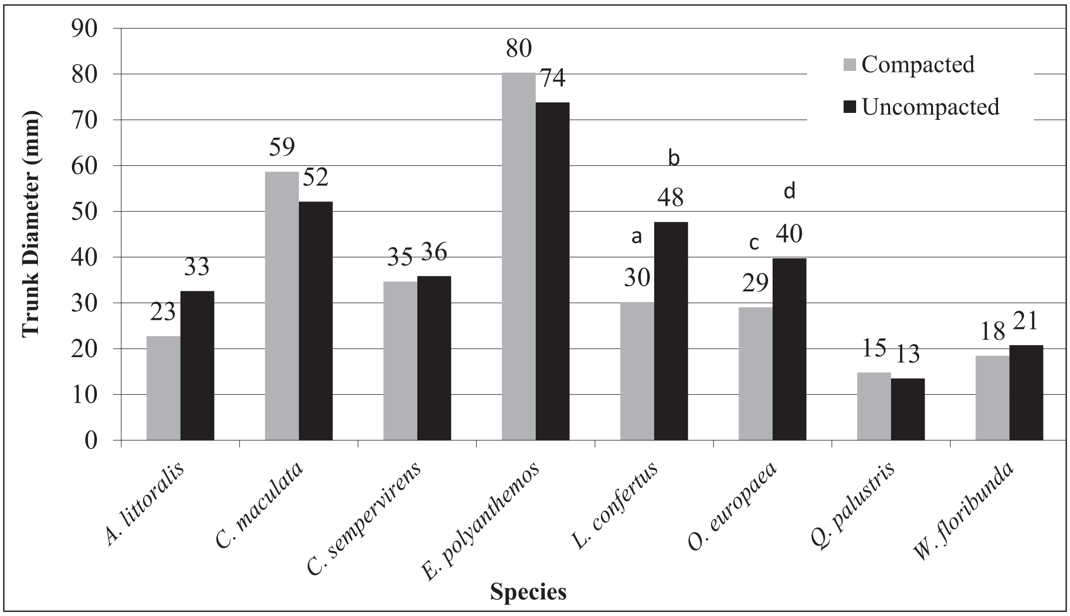

Figure 1. Mean trunk diameter after 20 months for all species grown in compacted and uncompacted soils. Letters denote significant difference (*P* < 0.05), and the number at the top each column is the value of the mean.

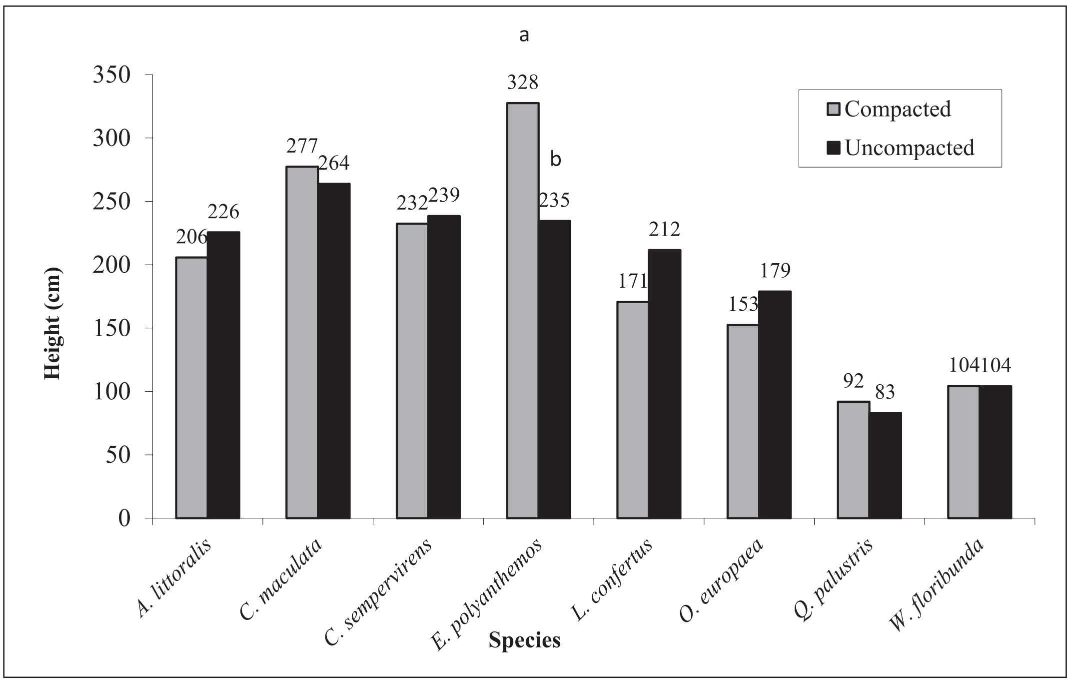

Figure 2. Mean tree height after 20 months for all species grown in compacted and uncompacted soils. Letters denote significant difference (*P* < 0.05), and the number at the top each column is the value of the mean.

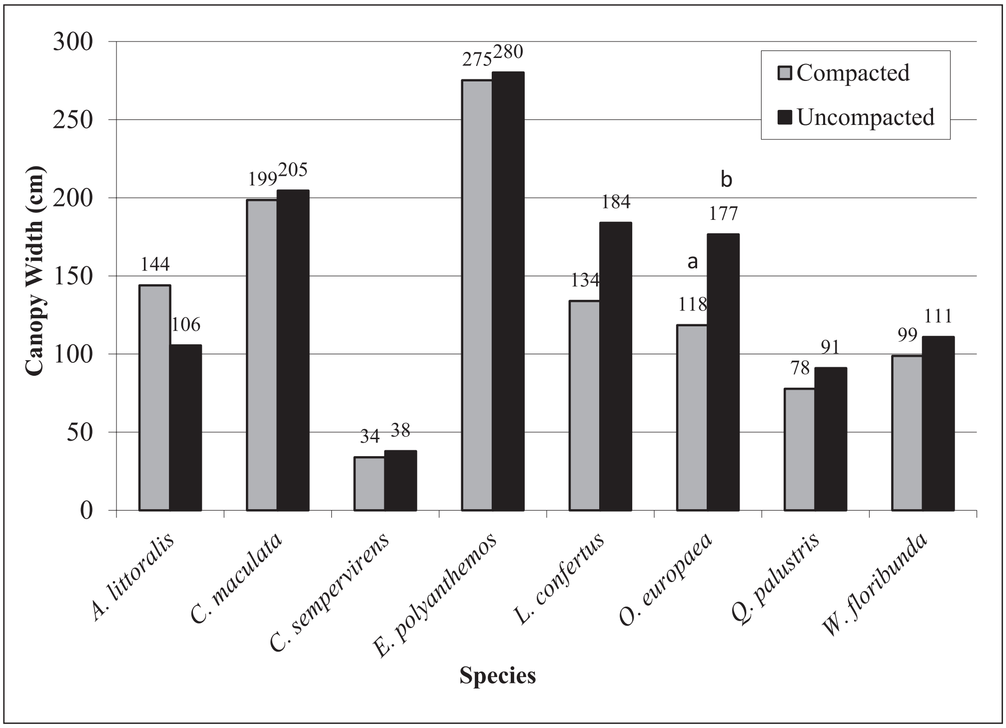

Figure 3. Mean full canopy width after 20 months for all species grown in compacted and uncompacted soils. Letters denote significant difference (*P* < 0.05), and the number at the top each column is the value of the mean.

Table 4. Overall root length for compass and treatment means. Means in the same row with a different letter are significantly different (*P* < 0.05). Compacted Direction LSD = 220.9. Direction LSD = 121.4.

	North	South	East	West
Compacted mean (mm)	1224	1078	1040	1056
Uncompacted mean (mm)	1209	1185	1027	1186
Compass mean (mm)	1216a	1131	1033b	1121

Table 5. Overall root length (mm) means for all species grown in compacted and uncompacted soils. Means in the same row of the species and separately for the compacted/uncompacted columns with a different letter are significantly different (*P* < 0.05). Species LSD = 305, Treatment LSD = 171, and Species Treatment LSD = 433

Species	Species	Uncompacted	Compacted
A. littoralis	441e	543p	339q
C. maculata	833cd	682p	984r
C. sempervirens	1454b	1434s	1474s
E. polyanthemos	2166a	2121t	2211t
L. confertus	1072c	1101r	1042r
O. europaea	1344b	1521s	1166r
Q. palustris	768d	807pu	728up
W. floribunda	927cd	1002r	851ur
Species and treatment mean	**1125**	**1152**	**1099**

uncompacted soil (Table 5). *A. littoralis* had the shortest root length of 441 mm, well below the second shortest, *Q. palustris*, of 768 mm. *E. polyanthemos* had the longest root length of 2,166 mm, followed by *C. sempervirens* with 1,454 mm. *C. maculata, C. sempervirens,* and *E. polyanthemos* had longer roots in compacted soil, while *O. europaea* had the significantly longer south-growing roots in uncompacted soil (Tables 5 and 6).

In general, root dry weights were heavier in uncompacted soil, but only significantly so for *O. europaea* ($P = 0.015$). *C. maculata* had a greater root mass in compacted soil (Table 7). The canopy mass for *L. confertus* was significantly heavier (1.41 kg) than the root mass in both compacted and uncompacted soil, and the uncompacted canopy was a significant 1.78 kg heavier than the compacted. *L. confertus* growing in uncompacted soil were a significant 1.07 kg heavier than those growing in compacted soil. For *O. europaea,* mean canopy mass was significantly greater than the root mass, and plant mass was significantly greater in uncompacted soil. *C. maculata*, *C. sempervirens,* and *E. polyanthemos* had significantly heavier canopy mass than root mass

Table 6. Species with significantly different mean root length (mm) for each treatment and compass bearing. Means in the same row with a different letter are significantly different ($P < 0.05$).

Species	North uncompacted	North compacted	South uncompacted	South compacted
C. sempervirens	1094a	1769b	1909	1410
O. europaea	1616	1174	1670a	992b

in both compacted and uncompacted soil. The root mass for *Q. palustris* was significantly heavier than the canopy mass in both compacted and uncompacted soil. The canopy mass for *W. floribunda* was significantly heavier than the root mass in uncompacted soil *(Table 7)*.

C. maculata had a significant difference in mean leaf area for compacted soil between north and west (LSD of 7.67), and leaf area on the north was 9.18 cm² larger than the leaves on the western side. For *L. confertus*, leaves on the eastern side of the canopy were significantly larger (8.67 cm²)($P = 0.029$) than the west in compacted soil, and the leaves on the south were significantly larger (9.28 cm²) than the north in uncompacted soil. *W. floribunda* had significantly larger leaves and leaf area on the east when compared with north, south, and west regardless of soil compaction. There was no significant treatment effect on chlorophyll fluorescence (Fv/Fm) for any of the species, and only *E. polyanthemos* and *L. confertus* were within the healthy range (0.78 to 0.85), with other species having readings for both compacted and uncompacted soil in the unhealthy/stressed range (0.71 to 0.77).

Survey

The Visual Tree Assessment form was completed for 76 trees, and REML analyses were performed on the Trunk Diameter, Height, and Canopy Width data. Trunk diameter is an indicator of rapid establishment (Figure 4), and REML analysis showed that, as expected, there were significant differences between species in mean trunk diameter ($P < 0.001$).

Table 7. Summary of canopy and root mass (kg) mean comparisons and canopy:root ratios for all species growing in compacted and uncompacted soils. For each species, means in the same column with a different letter are significantly different ($P < 0.05$). For *L. confertus* and *Olea europaea*, to simplify interpretation, paired letters (ab), (bc), (de), and (fg) are significantly different from each other ($P < 0.05$). The row mean allows total canopy and root mass regardless of soil treatment for species comparison, while the column mean is the total canopy and root mass for compacted versus uncompacted soils.

	Compacted	Uncompacted	Mean	Compacted	Uncompacted	Mean
		A. littoralis			*C. maculata*	
Canopy	0.40	0.59	0.49a	4.28a	2.31a	3.29a
Root	0.08	0.17	0.13b	0.94b	0.48b	0.71b
Mean	0.24	0.38		2.61	1.39	
Canopy:shoot ratio	3.83	4.23		4.87	5.35	
		C. sempervirens			*E. polyanthemos*	
Canopy	0.97a	1.15a	1.06a	11.09a	10.64a	10.87a
Root	0.24b	0.28b	0.26b	2.19b	2.87b	2.53b
Mean	0.60	0.71		6.64	6.76	
Canopy:shoot ratio	3.99	4.11		6.50	4.15	
		L. confertus			*O. europaea*	
Canopy	1.00a	2.78b	1.89d	0.94a	3.00b	1.97d
Root	0.31b	0.65c	0.48e	0.57	1.39c	0.98e
Mean	0.65f	1.72g		0.75f	2.19g	
Canopy:shoot ratio	4.35	3.79		1.52	1.99	
		Q. palustris			*W. floribunda*	
Canopy	0.16a	0.19a	0.17a	0.43	0.83a	0.63a
Root	0.29b	0.38b	0.33b	0.24	0.32b	0.28b
Mean	0.23	0.28		0.33	0.58	
Canopy:shoot ratio	0.52	0.45		2.01	2.31	

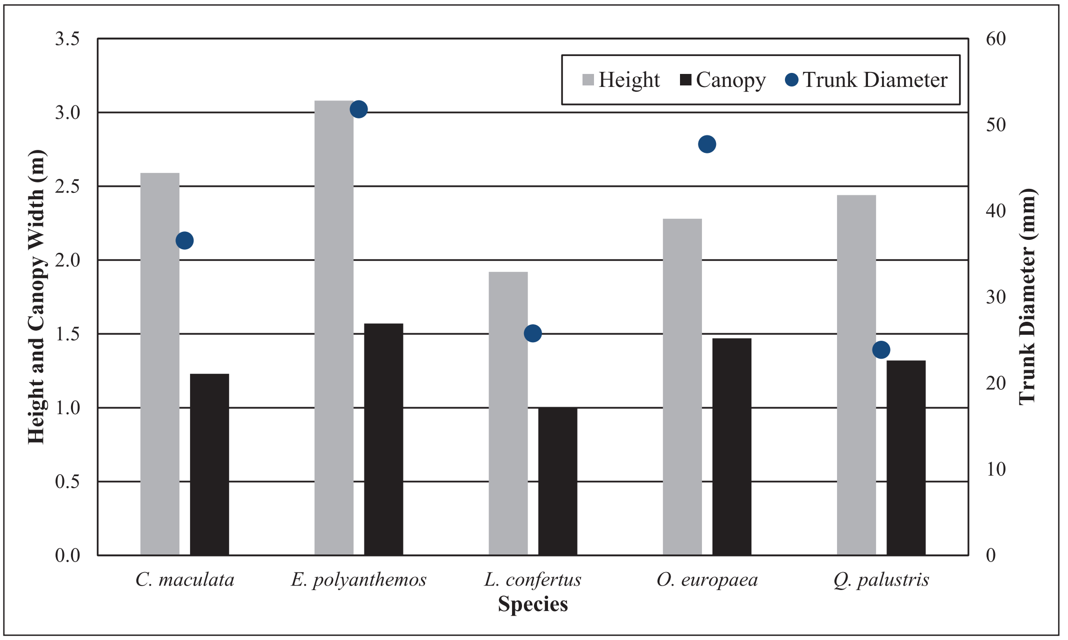

Figure 4. Mean trunk diameter, height, and canopy width for each species.

Separate LSDs for each species combination showed that there were eight species combinations which were significantly different from each other in trunk diameter (Table 8).

E. polyanthemos was the tallest tree with a mean height of 3.08 m, and *L. confertus* had the shortest mean height at 1.92 m (Figure 4). A REML analysis showed that species height differences were significant

Table 8. Species combinations which were significantly different in trunk diameter and height.

Species	Difference between trunk diameter means (mm)	LSD for trunk diameter for species combinations	Species with larger trunk diameter	Difference between tree height means (mm)	LSD for tree height for species combinations	Taller species
C. maculata – E. polyanthemos	15.24	9.63	*E. polyanthemos*	0.49	0.43	*E. polyanthemos*
C. maculata – L. confertus	10.78	9.98	*C. maculata*	0.67	0.44	*C. maculata*
C. maculata – O. europaea	11.19	9.32	*O. europaea*	N/A	N/A	N/A
C. maculata – Q. palustris	12.69	10.32	*C. maculata*	N/A	N/A	N/A
E. polyanthemos – L. confertus	26.02	10.27	*E. polyanthemos*	1.16	0.45	*E. polyanthemos*
E. polyanthemos – Q. palustris	27.93	10.60	*E. polyanthemos*	0.64	0.47	*E. polyanthemos*
L. confertus – O. europaea	21.97	9.98	*O. europaea*	N/A	N/A	N/A
O. europaea – Q. palustris	23.88	10.32	*O. europaea*	N/A	N/A	N/A
E. polyanthemos – O. europaea	N/A	N/A	N/A	0.80	0.43	*E. polyanthemos*
L. confertus – Q. palustris	N/A	N/A	N/A	0.59	0.48	*Q. palustris*

Table 9. Species combinations which were significantly different in mean canopy width.

Species	Difference between means (m)	LSD for species combination	Species with a wider canopy
C. maculata – E. polyanthemos	0.34	0.29	*E. polyanthemos*
E. polyanthemos – L. confertus	0.57	0.29	*E. polyanthemos*
L. confertus – O. europaea	0.47	0.29	*O. europaea*
L. confertus – Q. palustris	0.33	0.31	*Q. palustris*

($P = 0.001$). *E. polyanthemos* had the widest canopy of 1.57 m, *O. europaea* had a canopy width of 1.47 m, and L. confertus had the smallest width of 1 m (Figure 4). There were separate LSDs for each combination comparing two species. There were six combinations which had significantly different heights between species (Table 8). *E. polyanthemos* was significantly taller than the other four species. *C. maculata* was significantly taller than *L. confertus,* and *Q. palustris* was significantly taller than *L. confertus*.

A REML analysis for the north/south and east/west canopy widths showed a significant difference between species ($P = 0.008$). LSDs showed that there were four species combinations which had significantly different mean canopy widths (Table 9). *E. polyanthemos* had a significantly wider canopy than *C. maculata* and *L. confertus*. *L. confertus* was significantly smaller in canopy width than *O. europaea* and *Q. palustris*.

Tree condition data (Figure 5) showed that all species had mean scores above 18 out of 20 for root condition and ratings above 24 for trunk condition. For branch condition, *C. maculata* had a score of 43 out of 45, and *Q. palustris* had the lowest rating of 41. *O. europaea* had a perfect rating of 10 for foliage condition, and *E. polyanthemos* and *L. confertus* had the lowest rating of 7.

The soils of the survey sites are reactive clay soils derived from weathered basalt, and the lowest bulk density was 1.26 Mg/m^{-3}, which is not root limiting, and the highest was 1.75 Mg/m^{-3}, which may limit growth (Table 10). There were eight blocks of street trees which had a mean street reading of less than 2 MPa, and there were 13 blocks of street trees which had mean readings above 2 MPa. A REML analysis was performed on the data for bulk density and penetrative resistance.

For bulk density, the majority of the variation in data was between the left and right side soil sample of

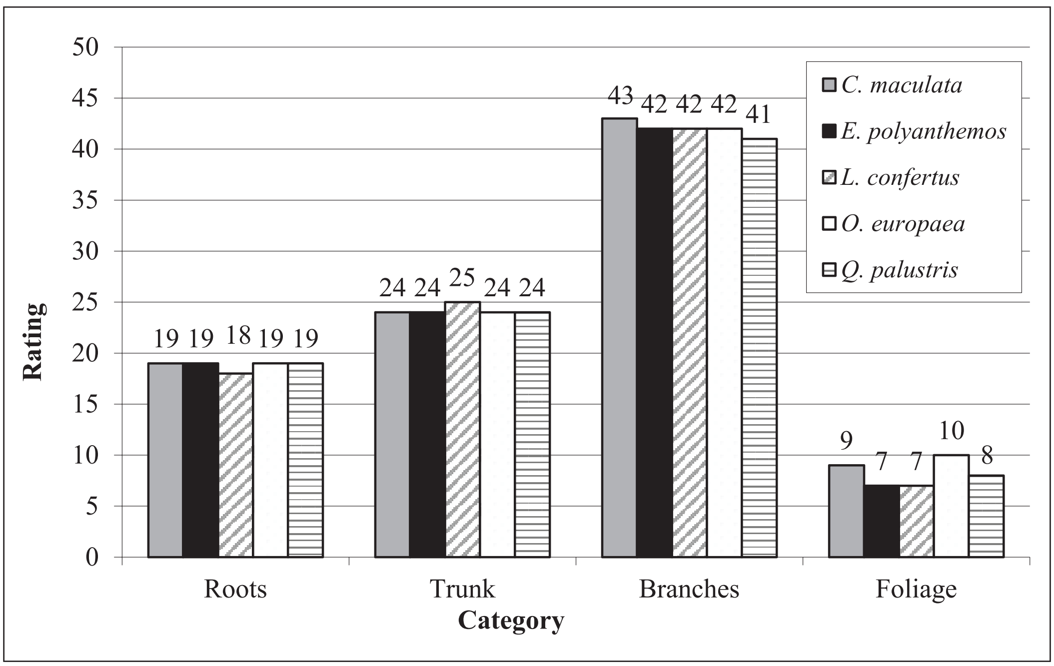

Figure 5. Tree condition rating category means for each species using the criteria from Table 1.

Table 10. Street range and means for bulk density (Mg/m^{-3}) and penetrative resistance (MPa).

Species	Bulk density range (Mg/m^{-3})	Mean bulk density (Mg/m^{-3})	Penetrative resistance range (MPa)	Mean penetrative resistance (MPa)
C. maculata	141–1.58	1.46	4.25–4.93	4.68
E. polyanthemos	1.45–1.64	1.49	2.70–4.91	3.89
L. confertus	1.28–1.55	1.45	1.34–3.66	1.92
O. europaea	1.26–1.50	1.42	1.05–1.85	1.53

Table 11. Variance components bulk density and penetrative resistance.

Measurement	Street	Address within street	Direction within address
Bulk density	10.8%	30.1%	59.1%
Penetrative resistance	21.9%	32.8%	45.3%

a tree (Table 11). The penetrative resistance data were similar to those for bulk density, with most of the variability being for samples taken around the same tree, indicated by direction within an address.

The Chlorophyll Fluorescence (Fv/Fm) for *E. polyanthemos* (0.83) and *O. europaea* (0.78) was within the range of a healthy tree. *C. maculata*, *L. confertus,* and *Q. palustris* had Fv/Fm readings just under 0.78, and REML analyses showed the majority of Fv/Fm variability was between the compass readings of the one tree.

DISCUSSION

After analysis, the eight species were placed into three categories. Category 1 (*C. maculata* and *E. polyanthemos*) trees increased growth in compacted soil, were more tolerant of soil compaction, and may not require soil amelioration prior to planting. Category 2 (*C. sempervirens*, *Q. palustris,* and *W. floribunda*) trees had growth unaffected by compacted soil, were tolerant of soil compaction, but may benefit from site amelioration to alleviate compaction for optimum growth. They will grow adequately if the soil remains compacted. Category 3 (*A. littoralis*, *L. confertus,* and *O. europaea*) trees had reduced growth in compacted soil, did not tolerate soil compaction, and site amelioration would be necessary for growth. These species may not be suitable for compacted soils (Fitzgerald 2012).

E. polyanthemos and *C. maculata* had the highest readings for each of the five measurements (tree height, canopy spread, trunk diameter, canopy mass, and root mass) and both species grew well in compacted and uncompacted soil. *E. polyanthemos, L. confertus, O. europaea, Q. palustris*, and *E. polyanthemos* trees were significantly taller in compacted soil. *L. confertu*s and *O. europaea* performed poorly in compacted soils, having significantly greater trunk diameters and canopy widths in uncompacted soil compared to compacted soil.

The tallest growing species was *E. polyanthemos,* while *L. confertus* was the shortest, with *C. maculata*, *O. europaea,* and *Q. palustris* ranging between. This impacts street tree selection, as rapid height growth is considered desirable, and so *E. polyanthemos* would be a preferred species choice. Given the tendency of *E. polyanthemos* and *O. europaea* to develop wider canopies, which are desirable in street trees, it is worth considering where they are planted in relation to infrastructure and the likelihood of more frequent pruning.

C. maculata, C. sempervirens, E. polyanthemos, *L. confertus*, and *Q. palustris* had significantly larger canopy mass means compared with root means in compacted soil, suggesting that compacted soil had a negative impact on root growth. All species except *A. littoralis* had a significant difference between the canopy and root uncompacted mean mass, and all species, apart from *Q. palustris,* had a higher mean canopy mass. *Q. palustris* had a greater mass below than above ground in both compacted and uncompacted soils.

This research confirms that *C. maculata* performs very well as an urban street tree. Many specimens were rated as being in outstanding condition, and it was the only species with a greater root mass in compacted than uncompacted soil, suggesting that it was establishing a substantial root system. *E. polyanthemos* has the ability to rapidly establish in compacted soil and was the tallest species with the widest canopy and largest trunk diameter. It was a good choice under these conditions for a rapid growing, easily-established street tree. However, having the longest roots of any species in both compacted and uncompacted soil, *E. polyanthemos* also has potential for damaging surrounding infrastructure earlier than other species.

O. europaea is regarded as being a resilient and adaptable urban tree in Melbourne, with this research confirming that it grows well in both compacted and uncompacted soils. However, the data show that it grows best and would establish more rapidly in uncompacted soils, so if rapid establishment and growth are desired, then it would be wise to ameliorate compacted sites. Similarly, the performance of *L. confertus* as a street tree will be enhanced if it is planted into uncompacted or ameliorated soils. If slower growth and establishment are tolerable, planting into compacted soils will provide a satisfactory outcome.

In compacted soil, *A. littoralis* was shorter with a wider canopy, which may be desirable in some landscapes. In such situations, soil compaction could be used to manipulate tree growth and development, which warrants further research. *A. littoralis* had the shortest, shallowest roots of the eight species in compacted and uncompacted soil, and as a consequence of this root architecture may cause less damage to surrounding infrastructure (Moore 2013).

C. maculata, C. sempervirens, and *E. polyanthemos* had longer roots growing in compacted soils compared to uncompacted soils, demonstrating that they were suitable choices for hostile soil conditions. *E. polyanthemos, L. confertus*, and *Q. palustris* had higher canopy:root ratios in compacted soil, meaning these species put on more canopy growth in compacted soil. For these and for other species which showed greater growth in compacted soils, such as *C. maculata, A. littoralis,* and *E. polyanthemos*, the increase in aboveground growth did not appear to come at the expense of root system establishment, allaying concerns that increased above-growth may mean that root systems were compromised by the retention of photosynthate in the aboveground parts of the plant. However, after 20 months, all trees were growing well and were in good condition.

C. maculata, *C. sempervirens,* and *E. polyanthemos* had longer roots in compacted soil, while *A. littoralis*, *L. confertus*, *O. europaea*, *Q. palustris,* and *W. floribunda* had longer roots in uncompacted soil, suggesting that they have reduced root growth in compacted soil. Roots were significantly longer in the northerly direction, probably due to higher soil temperatures from a lack of self-shading.

It is often assumed that trees will have smaller leaves if they are grown under stressful conditions. However, there was no difference between leaf sizes for trees growing in compacted and uncompacted soils. Indeed, trees growing in the compacted soils of Hume had larger leaves on average (for *O. europaea,* twice the size) than trees growing in the better quality and uncompacted soils of the Burnley field station, suggesting that leaf size is not a good indicator of environmental stress. Most of the trees had their largest leaves on the southern side of the canopy, which was exposed to lower levels of sunlight.

Bulk density data were collected outside the mulch placed around trees, as under the mulch the profile had been disturbed at planting, and lower bulk density readings were anticipated. To gain an accurate measure of site bulk density, data were collected from the undisturbed profile, which is where new root growth would occur during tree establishment. The bulk density and penetrative resistance data verified the significantly different levels of compaction for the compacted and uncompacted soils, but over the 20 months, the bulk density of the uncompacted soil remained constant, while that of the compacted soil reduced. It is possible that root penetration and ripping reduced bulk density, but it is well known that mulch can be a cost-effective remedy to soil compaction over the medium to long term (Scharenbroch et al. 2005; Urban 2008). This study supports this approach, but over a shorter period of 20 months.

Despite the soils of the survey being classed as compact to extremely compact (1.3 to 1.7Mg/m^{-3}) with often root growth limiting levels of penetrative resistance (1.3 to 4.9 MPa)(Roberts et al. 2006), the street trees were rated as being in outstanding or very good condition. Furthermore, most trees were symmetrical in canopy form, upright, and without trunk lean—all desirable characteristics of a good urban street tree. The data showing that there were considerable differences in compaction and penetrative resistance on different sides of the one street tree suggests that planting technique needs to be reviewed. The insertion and levering of the mechanical spade in creating the planting holes seemed to compact the soil on one side. Specifying that the sides of the planting holes need to be decompacted after planting should be written into future street tree planting contracts.

The Fv/Fm data which are indicative of photosynthetic efficiency showed no significant differences between species. A healthy tree should have Fv/Fm readings between 0.78 and 0.85 (Maxwell and Johnson 2000; Percival 2005). *E. polyanthemos* and *L. confertus* were within this range in compacted and uncompacted soils, but *C. maculata, O. europaea, Q. palustris*, and *W. floribunda* were below 0.78, indicating that they were unhealthy and stressed, which did not correspond with data suggesting that they were growing well. Data were collected over several days in mid-autumn to avoid the high levels of solar radiation and stress associated with summer. The Fv/Fm values often failed to correlate with the VTAs of the survey. While many trees were close to the 0.78 value for healthy trees, few achieved it. Some trees in excellent condition had ratios as low as 0.68, and clearly stressed trees ranged from 0.68 to 0.74, suggesting that further work is required to establish benchmark ratios for Fv/Fm for Australian species and conditions.

While comparisons between species were expected to reveal the significant differences between root and aboveground growth that the experiment and survey revealed, the data are important as they inform decisions about street tree selection. There are clear distinctions between which species grow fastest and which do better in compacted soils, and so certain species would be better choices than others for rapid and more cost-effective street tree establishment.

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ACKNOWLEDGEMENTS

Alicia Fitzgerald thanks Robert Bailey for his substantial assistance and Michael Leers, Senior Arborist at Hume Council. She also thanks her parents Peter and Marygabrielle Fitzgerald for their help and support throughout her PhD. Graham Hepworth of the Statistical Consulting Centre, University of Melbourne, greatly assisted in data analyses. Alicia Fitzgerald was supported by a University of Melbourne Postgraduate Research Scholarship.

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Résumé. Les conditions de croissance pour les racines d'arbres en alignement sont généralement sévères avec un espace souterrain restreint et des sols compactés par les infrastructures des chaussées et des trottoirs. Des plants de *Allocasuarina littoralis*, *Corymbia maculata*, *Cupressus sempervirens* var. *stricta*, *Eucalyptus polyanthemos*, *Lophostemon confertus*, *Olea europaea*, *Quercus palustris* et *Waterhousea floribunda* furent cultivés dans des carrés d'essai comportant des sols compactés pour certains et des sols non-compactés pour d'autres, pendant une période de vingt mois. La masse volumique apparente, la résistance à la pénétration des sols, la hauteur, l'étendue de la ramure, le diamètre du tronc, la surface foliaire et la fluorescence de la chlorophylle furent mesurés sur une base régulière. La biomasse des racines et des pousses fut mesurée après leur récolte. Puisque la masse volumique apparente des sols compactés en comparaison avec celle des sols non-compactés est un facteur de limitation pour la croissance des racines, une hypothèse fut formulée à l'effet que les espèces montreraient une croissance réduite dans les sols compactés. Toutefois, *C. maculata* et *E. polyanthemos* montrèrent une meilleure croissance, *C. sempervirens*, *Q. palustris* et *W. floribunda* eurent une bonne croissance tandis que *A. littoralis*, *L. confertus* et *O. europaea* montrèrent la pire performance sur les sols compactés. *E. polyanthemos*, *L. confertus* et *Q. palustris* obtinrent des ratios cime-racines plus élevés sur les sols compactés. *Q. palustris* possédait une plus grande biomasse dans le sol qu'en surface, ce qui présente des conséquences pour son utilisation lorsque l'espace souterrain est restreint. Dans le cadre d'une étude de terrain, des plants de *C. maculata*, *E. polyanthemos*, *L. confertus*, *O. europaea* et *Q. palustris* croissant en alignement furent examinés afin de déterminer leur taux d'établissement et de croissance sous des conditions urbaines. En outre des paramètres de sol et des arbres mentionnés ci-haut, une évaluation visuelle de l'arbre (EVA) fut effectuée. *E. polyanthemos* présenta les plus grandes mesures de diamètre du tronc, de hauteur et d'étendue de la ramure, montrant ainsi son potentiel pour un établissement rapide sur rues. Ce fut également la seule espèce à démontrer un plus grand ratio de surface foliaire dans les sols compactés. *E. polyanthemos* et *O. europaea* furent les seules espèces classées comme en santé sur le plan de la fluorescence de la chlorophylle, mais il n'y avait aucune différence significative sur ce plan que les sols soient compactés ou non. Une EVA démontra que *C. maculata* et *O. europaea* avaient la meilleure performance tandis que *E. polyanthemos, L. confertus*, et *Q. palustris* montrèrent une croissance réduite mais tout de même acceptable sur les sols compactés. Les sols étaient classés de non-salins à modérément salins et leur acidité variait de légère à forte. Tous les sols possédaient un certain degré de compaction et la résistance à la pénétration des racines était à des niveaux limitatifs. Les résultats obtenus suggèrent que la sélection rigoureuse des espèces et l'amélioration des sols, pour les espèces affectées par la compaction, pourraient faciliter l'établissement des arbres d'alignement.

Zusammenfassung. Die Wachstumsbedingungen für die Wurzeln von Straßenbäumen sind wegen begrenztem Raum und verdichtetem Boden durch die dortige Infrastruktur generell schwierig. *Allocasuarina littoralis, Corymbia maculata, Cupressus sempervirens* var. *stricta, Eucalyptus polyanthemos, Lophostemon confertus, Olea europaea*, *Quercus palustris*, und *Waterhousea floribunda* wurden für 20 Monate in verdichtetem und unverdichtetem Boden gezogen. Die Substratdichte und der penetrative Widerstand des Bodens, sowie Höhe, Kronenausdehnung, Stammdurchmesser, Blattfläche und Chlorophyllresistenz wurden regelmäßig gemessen. Da die Substratdichte von verdichteten Böden im Vergleich zu lockerem Boden das Wurzelwachstum limitiert, wurde hypothetisiert, dass Arten reduziertes Wurzelwachstum in kompakten Böden hätten. Dennoch, *C. maculata* und *E. polyanthemos* wuchsen besser, *C. sempervirens*, *Q. palustris,* und *W. floribunda* wuchsen gut und *A. littoralis*, *L. confertus,* und *O. europaea* hatten die schlechtesten Leistungen in verdichtetem Boden. *E. polyanthemos*, *L. confertus* und *Q. palustris* hatten ein höheres Kronen:Wurzel-Verhältnis in kompakten Böden. *Q. palustris* hatte eine größere Masse unter der Bodenoberfläche als oberhalb, was eine Implikation für die Verwendung an begrenzten Standorten hat. In einer Feldstudie wurden *C. maculata, E. polyanthemos, L. confertus, O. europaea*, und *Q. palustris,* als Straßenbäume wachsend, untersucht, um ihre Anwachsraten und das Wachstum unter urbanen Bedingungen zu bestimmen. Zusätzlich zu den weiter oben erwähnten Boden- und Baumparametern wurde eine Sichtkontrolle (VTA) durchgeführt. *E. polyanthemos* hatte den größten Stammdurchmesser, Höhe und Kronenausdehnung, was sein Potential für die rasche Standortetablierung in Straßen indiziert. Es war die einzige Art mit einer größeren durchschnittlichen Blattfläche in verdichtetem Boden. *E. polyanthemos* und *O. europaea* waren die einzigen Arten, die von der Chlorophyllfluorezenz als gesund klassifiziert wurden, aber es gab keine signifikanten Differenzen in der Fluoreszens zwischen lockeren und verdichteten Böden. Die Sichtkontrolle (VTA) zeigte, dass *C. maculata* and *O. europaea* am besten abschnitten und dass *E. polyanthemos, L. confertus*, und *Q. palustris* zwar reduziertes, aber akzeptables Wachstum in kompakten Böden zeigten. Die Böden rangierten von nicht salin bis moderat salin und waren leicht bis stark sauer. Alle Böden waren bis zu einem bestimmten Grad verdichtet und die penetrative Resistenz lag im Bereich der Wurzelbegrenzung. Die Ergebnisse zeigen, dass sorgfältige Artenauswahl und Bodenverbesserung für die Arten, die anfällig für die Auswirkungen von Verdichtung sind, die Standortetablierung verbessern würde.

Resumen. Las condiciones de crecimiento de las raíces de los árboles de la calle son generalmente duras, con espacios restringidos y suelos compactados de la infraestructura del paisaje urbano. Se cultivaron ejemplares de *Allocasuarina littoralis, Corymbia maculata, Cupressus sempervirens* var. *stricta, Eucalyptus polyanthemos, Lophostemon confertus, Olea europaea, Quercus palustris* y *Waterhousea floribunda* en suelos compactos y no compactos durante veinte meses en bloques experimentales. Se midieron regularmente la densidad aparente, resistencia a la penetración de los suelos, altura y extensión del dosel, diámetro del tronco, área foliar y fluorescencia de clorofila. La biomasa de raíces y brotes se determinó después de la cosecha. Dado que la densidad aparente del suelo compactado en comparación con el no compactado limitaba el crecimiento de las raíces, se planteó la hipótesis de que las especies habrían reducido el crecimiento en los suelos compactados. Sin embargo, *C. maculata* y *E. polyanthemos* crecieron más, *C. sempervirens, Q. palustris* y *W. floribunda* crecieron bien, y *A. littoralis, L. confertus* y *O. europaea* tuvieron el peor desempeño en suelos compactados. *E. polyanthemos, L. confertus* y *Q. palustris* tuvieron una mayor proporción de dosel: raíz en el suelo compactado. *Q. palustris* tenía mayor masa bajo tierra que arriba, lo que tiene implicaciones para su uso en sitios confinados. En un estudio de campo, *C. maculata, E. polyanthemos, L. confertus, O. europaea* y *Q. palustris*, creciendo como árboles de la calle, fueron evaluados para determinar sus tasas de establecimiento y crecimiento en condiciones urbanas. Además de los parámetros del suelo y del árbol mencionados anteriormente, se realizó una Evaluación Visual (VTA). *E. polyanthemos* tenía el mayor diámetro, altura y extensión del dosel del tronco, lo que indica su potencial de establecimiento rápido en las calles y fue la única especie con un área foliar media mayor en suelo compactado. *E. polyanthemos* y *O. europaea* fueron las únicas especies clasificadas como sanas por fluorescencia de clorofila, pero no hubo diferencias significativas en la fluorescencia entre suelos compactados y no compactados. VTA mostró que *C. maculata* y *O. europaea* tuvieron un mejor desempeño y que *E. polyanthemos, L. confertus* y *Q. palustris* tuvieron un crecimiento reducido pero aceptable en el suelo compactado. Los suelos variaron de no salinos a moderadamente salinos y fueron levemente a fuertemente ácidos. Todos los suelos fueron compactados hasta cierto punto y la resistencia a la penetración estaba en niveles limitantes de la raíz. Los resultados sugieren que la selección cuidadosa de las especies y la mejora del suelo para las especies propensas a los efectos de la compactación facilitarían el establecimiento de árboles en las calles.