

THE INFLUENCE OF COMPACTION AND SOIL STRENGTH ON THE ESTABLISHMENT OF FOUR AUSTRALIAN LANDSCAPE TREES

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Abstract. Two experiments were conducted to test the hypothesis that trees able to establish in urban soils will have a higher-than-average tolerance to the higher mechanical impedance and soil strength of compacted soils. Experiment 1 tested the ability of the roots of *Corymbia maculata* (spotted gum, syn. *Eucalyptus maculata*), *Lophostemon confertus* (brush box), *Corymbia ficifolia* (red flowering gum, syn. *Eucalyptus ficifolia*), and *Agonis flexuosa* (willow myrtle) seedlings to penetrate a sandy loam soil compacted to bulk densities of 1.4 and 1.8 mg · m⁻³ at 13% gravimetric moisture content. While roots of all species were able to penetrate the soil at the higher bulk density, total root penetration depth was reduced by 60% in all four species. Experiment 2 tested the ability of *Corymbia maculata* and *C. ficifolia* to penetrate soil compacted at bulk densities 1.4, 1.6, and 1.8 mg · m⁻³ at two moisture levels, 7% and 10% gravimetric moisture. At 7% moisture, both species were able to penetrate soil compacted to 1.4 and 1.6 mg · m⁻³, but neither species was able to successfully penetrate soil compacted to 1.8 mg · m⁻³. At 10% moisture, both species were able to penetrate soil compacted to 1.4 and 1.6 mg · m⁻³. They also were able to successfully penetrate soil compacted to 1.8 mg · m⁻³, although with significantly less depth of penetration than at the two lower bulk densities.

Key Words. Soil compaction; urban soils; *Corymbia maculata*; *Lophostemon confertus*; *Agonis flexuosa*; *Corymbia ficifolia*; root growth; tree establishment.

In the urban environment, arborists and horticulturists often have the task of establishing trees under less than optimal conditions for root growth. Urban soils can impose serious constraints on tree establishment and growth, due to their impact on root growth and function. Urban soils are those that have been disturbed and changed by the processes involved in the development of the urban infrastructure (Craul 1992).

Soil compaction, which occurs when pressure is applied to a soil surface, as a result of vehicular or pedestrian traffic, is common in urban soils. Compaction changes the physical properties of soils by in-

creasing their bulk density and strength, and by reducing porosity. Compaction may cause reduced infiltration rates of water, poor drainage, reduced availability of water, and reduced air and oxygen supply to roots (Handreck and Black 1994). Because these conditions may modify root growth, and because they may be experienced simultaneously in compacted soil, it is often difficult to differentiate between their effects (Scott-Russell 1977).

Soil compaction has been documented in many urban soils (Patterson 1976; Jim 1998) and is acknowledged as a major impediment to establishment of trees in urban areas. Soil compaction leads to reduced root growth and, as a result, the growth of woody plants is inhibited. Reduced growth of seedlings in compacted soils has been demonstrated in studies of many species of trees (Zisa et al. 1980; Pan and Bassuk 1985; Gilman et al. 1987). Trees growing in compacted urban soils may be subject to seasonal cycles of high and low soil strength as these soils dry out and are wetted again.

This study tested the effects of commonly encountered levels of soil compaction on root growth in four Australian native tree species. The two experiments reported here test the hypothesis that trees able to establish in urban soils will have a higher-than-average ability to overcome the higher mechanical impedance and soil strength of compacted soils.

MATERIALS AND METHODS

Experiment 1

Seeds of four Australian native species, spotted gum (*Corymbia maculata*, syn. *Eucalyptus maculata*), brush box (*Lophostemon confertus*), willow myrtle (*Agonis flexuosa*), and red flowering gum (*Corymbia ficifolia*, syn. *Eucalyptus ficifolia*) were germinated on a sandy loam soil compacted to a bulk density of 1.4 and 1.8 mg · m⁻³, at 13% gravimetric moisture content, and seedling root penetration and growth were assessed. These species were chosen because they are common

urban trees in Australia. Field observation suggests that the four species tested have a range of tolerances to urban soils, with *C. maculata* > *Lophostemon confertus* > *Agonis flexuosa* > *C. ficifolia*.

Construction of the compacted profiles. Sandy loam soil (7.6% clay, 6.6% silt, 36.6% fine sand, and 50.8% coarse sand) of pH 4.5 and electrical conductivity 28.5 dS/m was used to construct the compacted soil profiles. The soil was brought to 13% gravimetric moisture content prior to compaction. The different bulk densities were achieved by compacting different weights of soil to a single volume.

The soil was compacted into cylinders of commercial uPVC stormwater pipe with average internal diameter of 105 mm (4 in.), cut into 150 mm (6 in.) lengths. Prior to filling and compaction, a separator disc of metal (25 mm [1 in.] thick, 103 mm [4 in.] in diameter) was placed at the bottom of the tube. This provided a uniform space of 25 mm in the top of each tube once it was inverted after compaction, into which seeds could be sown. The tubes were compacted individually, being placed in a metal mold, with an overflow tube on top of the mold. The soil was compacted using a jackhammer with a 105-mm-diameter disc on the end, which pounded soil in the top of the overflow tube. After filling and compaction, tubes were placed in plastic bags and secured to prevent moisture loss.

Seed sowing. Seeds were placed directly onto the surface soil. For each species and bulk density combination, there were five replicates. Germination percentages for the test species were determined by growing seed in a petri dish with moistened filter paper, in a growth chamber (Conviron Controlled Growth Chamber, Model EF7) at 22°C (71.6°F), with 12 hours light and 12 hours dark. After determining germination percentages for the test species, seed of each was sown onto the top of the tubes to give a maximum of 10 seedlings. For spotted gum and red flowering gum, 20 seeds were sown on each tube. For brush box and willow myrtle, weighed samples of seed (0.1 and 0.03 g, respectively) were sown on each tube, the weight of seed having been calculated to give at least 20 germinants per tube. The plastic bags placed on the tubes of soil when the soil was compacted were left on the tubes during the time in the growth chamber, again to minimize soil drying during the study period. Each tube was ini-

tially at 13% moisture and, at sowing, tubes were watered with four sprays (approximately 4 mL [0.14 oz] water) from a handheld sprayer, and then an extra two sprays every second day, to allow for germination. Seed was sown in June 1995 and the tubes placed in the growth chamber. Spotted gum was grown for 21 days under these conditions, brush box for 27 days, red flowering gum for 20 days, and willow myrtle for 29 days.

Measurements of root penetration depth and shoot height were made for each seedling that penetrated the soil profile. Seedlings that grew in the interface of the soil and the tube wall were discarded. Root depth was assessed by measuring the distance from the root tip to the base of the seed, or to the point at which surface growth became vertical. Shoot height was measured from the top of the cotyledons (unexpanded or expanded) to the base of the seed.

Experiment 2

Seedlings of two Australian native species, spotted gum and red flowering gum, were grown in cylinders of sandy loam compacted to bulk densities of 1.4, 1.6, or 1.8 mg · m⁻³, at two soil moisture levels, 7% and 10% gravimetric moisture content. The soil profiles were compacted as for Experiment 1. Pre-germination treatments of 48 hours in aerated water for spotted gum and 24 hours in aerated water for red flowering gum were used. These treatments were determined by means of trials for each species to determine germination under various conditions. For each species, a seed lot was pre-germinated and when the seed had chitted (the radicle just beginning to emerge), 20 germinating seeds were placed on top of the soil in each tube, to give a maximum of 10 seedlings. For each species, bulk density treatment, and moisture combination, there were five replicates. Chitted seed of both species was placed into the growth chamber in November 1995 and grown for 22 days (spotted gum) and 26 days (red flowering gum). Conditions of growth were as for Experiment 1, but no additional water was added to the tubes during the trial, so as not to modify soil strength. Measurements were made of root penetration depth and shoot height as in Experiment 1.

Soil strength characteristic curves of moisture versus penetrative resistance at bulk densities 1.4, 1.6, and 1.8 mg · m⁻³ were generated for the soil

used in this experiment. Penetrative resistance was measured using a handheld pocket penetrometer (model CL-700A, Soiltest, Inc., P.O. Box 8804, Lake Bluff, IL, US).

RESULTS

Compaction Experiment 1

Germination and penetration of seedlings. The percentages of seedlings that germinated and then penetrated the soil for the various species and treatment combinations in Experiment 1 are shown in Table 1. No statistical analysis of these percentages was done. It was not possible to calculate percentage germination rates for weighed samples because the total number of seeds in the sample was unknown due to the small size of the seed.

Surface rooting. All species in Experiment 1 exhibited surface rooting, where after germination, the radicle grew along the surface of the soil, sometimes with growth of very fine secondary roots.

Root penetration depth. The data and analysis of root penetration depth are for penetrants only. That is, roots had actually penetrated the soil. Because the root depth data were not normally distributed and there was not constant variance between treatments, data were analyzed using nonparametric statistics (Kruskal-Wallis and Mann-Whitney tests). Nonparametric statistics involve calculation and analysis of median values for data. *P* values were calculated for comparisons of medians at the 95% confidence level, with *P* values with a significant difference being $P < 0.05$.

In all species, the increase in bulk density from 1.4 to 1.8 $\text{mg} \cdot \text{m}^{-3}$ produced a uniform reduction in root growth of approximately 60% (Figure 1). There was a difference in root penetration depth between bulk density 1.4 and 1.8 $\text{mg} \cdot \text{m}^{-3}$ for all species (Figure 1). However, the *P*-value for red flowering gum should be interpreted cautiously because of the differences in the sample size (*N*) between these treatments (Table 1).

Shoot height. Shoot height data were normally distributed, with constant variance between treatments; therefore, analysis of variance and two sample t-tests were used to test for a difference between the means at the 95% confidence interval.

The only species to show a difference for shoot height were brush box (1.1 mm) and willow myrtle

Table 1. The percentage and mean number of seeds that germinated and penetrated in the soil cores, at 13% gravimetric moisture content. *N* = number of replicates between samples used in data analysis.

Bulk density ($\text{mg} \cdot \text{m}^{-3}$)	Species			
	Spotted gum	Red flowering gum	Brush box	Willow myrtle
Percentage of seeds that germinated			Mean no.	Mean no.
1.4	40%	94%	27.0 ^z	15.6 ^z
1.8	40%	86%	28.0 ^z	12.2 ^z
Percentage of germinants that penetrated the soil cores				
1.4	48% (<i>N</i> = 24)	48% (<i>N</i> = 23)	NA ^y (<i>N</i> = 50)	NA ^y (<i>N</i> = 50)
1.8	32% (<i>N</i> = 16)	10% (<i>N</i> = 5)	NA ^y (<i>N</i> = 50)	NA ^y (<i>N</i> = 50)

^zWeighed sample, giving at least 20 germinants. Brush box, 0.1 g, willow myrtle 0.03 g.

^yNA Weighed sample, maximum of 10 penetrants chosen for measurement.

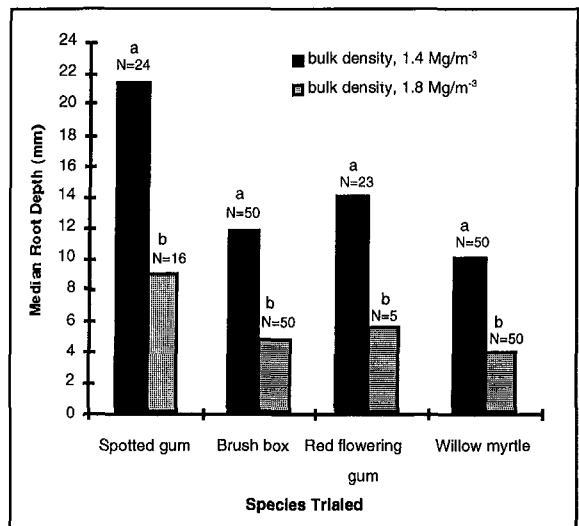


Figure 1. Median root depth for species trialed at bulk density 1.4 and 1.8 $\text{mg} \cdot \text{m}^{-3}$ and 13% moisture. Differing letters between bulk densities for a species denote significant median differences at $P < 0.05$.

(1.7 mm) (data not shown). Red flowering gum and spotted gum showed no difference in shoot height. However, the *P* values should be interpreted cautiously because of the differences in *N* between treatments for red flowering gum. However, given seedling variation, it is unlikely that these differences are biologically significant. Because of the short du-

ration of this experiment, seedling height was probably predetermined by cell division in the embryo rather than by soil bulk density.

Compaction Experiment 2

Germination and penetration of seedlings. The percentages of just-germinated seedlings that survived and then penetrated the soil for the different species and treatment combinations of Experiment 2 are shown in Table 2. Germination of seedlings and penetration of the soil cores were variable within moisture and bulk density combinations for each species.

Surface rooting. All species in Experiment 2 exhibited surface rooting, as in Experiment 1.

Root penetration depth. The data and analysis of root depth given are for penetrants only; that is, seedlings whose roots had actually penetrated the soil. The statistical analysis should be considered in the light of the percentage of seedlings that germinated and the percentage of these that went on to penetrate the soil cores (Table 1). The data were analyzed as for data in Experiment 1.

With spotted gum, as soil moisture increased for a given bulk density level, the median root depth increased. There was a difference in root depth at each bulk density level between 7% and 10% moisture (Figure 2). For root depth between the three bulk densities at 7% moisture, there was a difference between bulk density 1.4 and 1.8 $\text{mg} \cdot \text{m}^{-3}$, and 1.6 and 1.8 $\text{mg} \cdot \text{m}^{-3}$ (Figure 3). Comparison of root depths between the three levels of bulk density at 10% moisture indicated a difference between all bulk density combinations (Figure 3).

For red flowering gum, comparison of root depth between 7% and 10% moisture within the three levels of bulk density indicates a difference in root depth at bulk density 1.4 $\text{mg} \cdot \text{m}^{-3}$ only (Figure 2). Comparison of root depth between the three levels of bulk density at 7% indicated no difference in root depth between bulk density 1.4 and 1.6 $\text{mg} \cdot \text{m}^{-3}$ (Figure 3). There was, however, a difference between bulk density 1.4 and 1.8 $\text{mg} \cdot \text{m}^{-3}$, and between 1.6 and 1.8 $\text{mg} \cdot \text{m}^{-3}$. Comparison of root depth between the three levels of bulk density at 10% moisture

indicated no difference between bulk density 1.4 and 1.6 $\text{mg} \cdot \text{m}^{-3}$. There was a difference between bulk density 1.4 and 1.8 $\text{mg} \cdot \text{m}^{-3}$ and between 1.6 and 1.8 $\text{mg} \cdot \text{m}^{-3}$.

Shoot height. Shoot height data was analyzed as per shoot data in Experiment 1.

Table 2. Percentages of germinants that survived and that penetrated the soil cores, and N, the number of replicates (N) between 7% and 10% moisture within the various bulk densities for spotted gum and red flowering gum.

Bulk density ($\text{mg} \cdot \text{m}^{-3}$)	Species			
	% of germinants surviving		% of germinants that penetrated soil cores	
	Spotted gum	Red flowering gum	Spotted gum	Red flowering gum
<i>Moisture (7%)</i>				
1.4	47%	36%	22% (N = 9)	22% (N = 4)
1.6	37%	9%	32% (N = 16)	8% (N = 7)
1.8	25%	7%	42% (N = 16)	10% (N = 4)
<i>Moisture (10%)</i>				
1.4	59%	46%	94% (N = 7)	58% (N = 29)
1.6	75%	58%	96% (N = 46)	84% (N = 39)
1.8	89%	52%	100% (N = 50)	78% (N = 40)

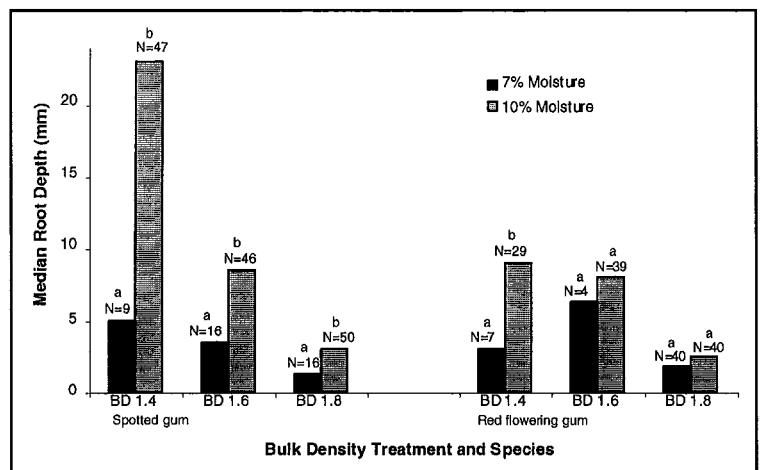


Figure 2. Median root depth versus bulk density treatment at 7% and 10% moisture for spotted gum and red flowering gum. Differing letters between soil moisture content for each bulk density level denote significant median differences at $P < 0.05$.

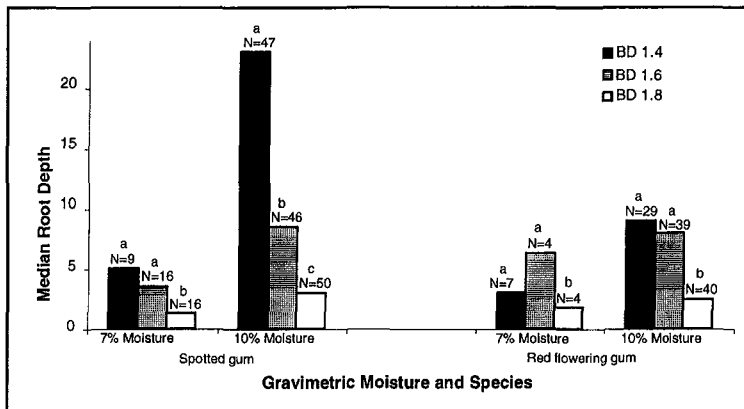


Figure 3. Median root depth versus gravimetric moisture content for spotted gum and red flowering gum. Differing letters between bulk density for each moisture level denotes significant median differences at $P < 0.05$.

For spotted gum, shoot height was higher for each bulk density treatment at 10% moisture than at 7%. There was no difference in shoot height within the three bulk density levels at 7% and 10% moisture.

For red flowering gum, shoot height was higher for each bulk density treatment at 10% moisture than at 7%. There was no difference in shoot height within the three bulk density levels at 7% and 10% moisture. Comparison of shoot height within the three levels of bulk density at 10% moisture showed a difference in shoot height between bulk density 1.6 and 1.8 $\text{mg} \cdot \text{m}^{-3}$ only.

DISCUSSION

Bulk densities of 1.8 $\text{mg} \cdot \text{m}^{-3}$ and above are common in the urban environment (Patterson 1976; Craul 1992; Randrup 1998) and have been shown to limit root growth (Zisa et al. 1980; Gilman et al. 1987). Data from this experiment show that even when moisture is high, a 60% reduction in root growth may be expected for a range of species at high levels of soil compaction. At bulk density 1.8 $\text{mg} \cdot \text{m}^{-3}$ and 13% moisture, the penetrative resistance of this soil was approximately 1.5 MPa, which is greater than the 1 MPa (Cass et al. 1993) suggested as the upper limit for unrestricted root growth. At bulk density 1.4 $\text{mg} \cdot \text{m}^{-3}$ and 13% moisture, the penetrative resistance of this soil was 0.05 MPa, which would not limit root growth.

Wide variation in root penetration depth was found, particularly in less compacted soils (1.4

$\text{mg} \cdot \text{m}^{-3}$, for Experiment 1, and 1.4 and 1.6 $\text{mg} \cdot \text{m}^{-3}$ for Experiment 2). The variation in root penetration at low bulk density may be assumed to be due to seedling vigor. There was generally less variation in root penetration depth at bulk density 1.8 $\text{mg} \cdot \text{m}^{-3}$ in both experiments. Variation in root penetration at high bulk density may be more important because it suggests that individual plants are capable of rooting in soils too dense for the majority of the population (Heilman 1981). These plants would then have an advantage if their roots were not able to follow soil cracks or zones of lower resistance at the interface of the soil and the root ball

during establishment.

Small increments in bulk density may reduce root growth, and even at low bulk densities, root growth may be restricted as the soil dries out and mechanical impedance increases (Heilman 1981).

All species in both experiments exhibited surface rooting. This phenomenon was usually greater at bulk density 1.8 $\text{mg} \cdot \text{m}^{-3}$. Following germination, the seedling root was deflected by the soil and grew laterally until locating a point in the compacted profile where it could penetrate. Surface root growth was greatest in Experiment 2, in the drier soil, where the germinating roots were less able to find weaker points in the profile for penetration. Spotted gum showed the greatest tendency for surface rooting in both trials; brush box and willow myrtle showed the least tendency for this behavior. This may in part be due to differences in radicle diameter. Willow myrtle had the smallest radicle diameter, spotted gum and red flowering gum had the largest diameter roots, with brush box intermediate.

The stimulation of lateral rooting with increasing restriction of downward root penetration at high bulk density has been noted previously (Heilman 1981). This phenomenon is an extension of the tendency of tree roots to grow where there is least mechanical resistance to elongation. In compacted field soils, this often means that roots are confined to cracks or planes of weakness in or between peds (Heilman 1981). If the root system continues to develop in highly compact soils, then laterals may

comprise a larger percentage of total root weight than is usual in less compact soils (Pan and Bassuk 1985), and the whole root system may be shallower (Gilman et al. 1987).

In Experiment 2, 7% soil moisture content was limiting to both seedling survival and soil penetration, compared to the 10% moisture regime (Table 2).

At 7% moisture and bulk density $1.6 \text{ mg} \cdot \text{m}^{-3}$, the penetrative resistance was 1.7 MPa, still within a range over which root growth can occur; however, at bulk density $1.8 \text{ mg} \cdot \text{m}^{-3}$, penetrative resistance was between 3.5 and 4.0 MPa, above the range where severe restrictions of root growth occurs. At 10% moisture, the penetrative resistance at $1.8 \text{ mg} \cdot \text{m}^{-3}$ was 3.4 MPa, while values for bulk densities 1.4 and $1.6 \text{ mg} \cdot \text{m}^{-3}$ were both less than 1 MPa.

The lower numbers of seedlings penetrating the cores in Experiment 2, under the 7% moisture regime, confuse the results by limiting the number of replicates and the inferences that can be made from analysis of the data. Spotted gum conformed to expectations of root growth responses in terms of the critical levels of penetrative resistance, with an increase in root penetration depth between 7% and 10% moisture for each of the bulk density treatments. Red flowering gum did not conform to these expectations, having fewer penetrants at the 7% moisture level, making analysis of the root growth data inconclusive. At 10% moisture, red flowering gum had enough penetrants to make valid inferences, and it conformed more with expectations regarding critical penetrative resistance values at the different bulk density levels.

The root growth data confirm other findings that root growth can continue and allow establishment on compacted urban soils maintained at high levels of available water (Zisa et al. 1980). Zisa et al. (1980) found that only on a silt loam soil, with a bulk density of $1.8 \text{ mg} \cdot \text{m}^{-3}$ was seedling establishment reduced. Their critical penetrative resistance increment for root growth was between 1.4 and 2.4 MPa in sandy loam and silt loam. At 7% moisture in Experiment 2, the penetrative resistance of the soil compacted to $1.6 \text{ mg} \cdot \text{m}^{-3}$ falls within this range.

Urban soils can be expected to provide an extremely varied environment for root growth in terms of soil properties such as texture, compaction, and

soil strength. Where soil compaction is above critical limits, root proliferation can be expected to be poor or to cease until conditions are modified by an increase in moisture, decreasing soil strength. However, soil moisture must not be high enough to limit root growth by creating anaerobic conditions.

CONCLUSIONS

In moist soil, an increase in soil bulk density from 1.4 to $1.8 \text{ mg} \cdot \text{m}^{-3}$ significantly reduced the depth of root penetration in a sandy loam soil. The extent of restriction of root penetration was similar for all four species tested. Where soil moisture was 7% or 10%, the same phenomenon was observed for *Corymbia maculata* and *C. ficifolia*. However, at the lower soil moisture content, the effect of bulk density was exacerbated as a result of increased soil strength. Overall root growth in the more compacted soils was similar for the two species at both moisture levels.

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Résumé. Une expérience d'inondation a été menée afin de tester la capacité d'arbres récemment plantés à former de nouvelles racines sous des conditions d'inondation ainsi qu'à se remettre d'une inondation. Des *Corymbia maculata* (syn. *Eucalyptus maculata*), des *Lophostemon confertus*, des *Platanus orientalis* et des *Platanus* \forall *acerifolia* ont été soumis à une période d'inondation et à une phase de reprise après que l'inondation eu cessé. La longueur des racines a été mesurée à la fois à la fin de la période d'inondation et à celle de la phase de reprise. Les différentes espèces ont réagi de façon considérablement différentes dans leur capacité à tolérer et à se remettre d'une période d'inondation. L'inondation a supprimé la croissance des racines et des pousses chez toutes les espèces expérimentales. Le *Corymbia* et le *Platanus orientalis* ont été capable d'initier de nouvelles racines sous des conditions d'inondation, contrairement au *Platanus* \forall *acerifolia* et au *Lophostemon confertus*.

Zusammenfassung. Es wurden zwei Experimente durchgeführt, um die Hypothese zu testen, daß Bäume, die sich an urbanen Standorten etablieren können, eine höhere Toleranz gegen mechanische Einflüsse und Bodenstärke von trockenen verdichteten Böden haben. Das erste Experiment testete die Fähigkeiten der Wurzeln von Sämlingen von *Corymbia maculata*, *Lophostemon confertus*, *Corymbia ficifolia* und *Agonis flexuosa*, einen sandigen Lehmboden zu durchdringen, der eine Dichte von 1,4 und 1,8 mg · m⁻³ bei 13 % gravimetrischem Feuchtegehalt aufweist. Während die Wurzeln von allen Species in der Lage waren, den Boden bei einer höheren Körperdichte zu durchdringen, lag der totale Anteil der Wurzeldurchdringung reduziert bei 60 % bei allen vier Baumarten. Das zweite Experiment testete die Fähigkeit von *Corymbia maculata* und *C. ficifolia* einen verdichteten Boden mit einer Körperdichte von 1,4 und 1,8 mg · m⁻³ bei zwei Feuchtegehalten, 7 und 10 % gravimetrische Feuchte, zu durchdringen. Bei 7 % Feuchte waren beide Arten fähig den Boden bei 1,4 und 1,6 mg · m⁻³ zu durchdringen, aber nicht bei 1,8 mg · m⁻³. Bei 10 % Feuchte konnten beide Arten den Boden bei 1,4 und 1,6 mg · m⁻³ durchdringen. Sie waren ebenso in der Lage, erfolgreich einen verdichteten Boden mit 1,8 mg · m⁻³ zu durchwurzeln, obwohl hier deutlich geringere Durchwurzlungsteifen erreicht wurden als bei den beiden anderen Böden.

Resumen. Se llevaron a cabo dos experimentos para probar la hipótesis de que los árboles capaces de establecerse en suelos urbanos tendrán una mejor tolerancia promedio a una mayor impedancia mecánica y resistencia de los suelos compactados. Un experimento probó la habilidad de las raíces de los brinzales de *Corymbia maculata* (Sin. *Eucalyptus maculata*), *Lophostemon confertus*, *Corymbia ficifolia* (Sin. *Eucalyptus ficifolia*) y *Agonis flexuosa*, para penetrar suelos franco arenosos compactados con densidades aparentes de 1.4 y 1.8 mg/m³ al 13% de contenido de humedad gravimétrica. Mientras las raíces de todos los árboles fueron capaces de penetrar los suelos de mayor densidad, la profundidad total de penetración se redujo en un 60% en las cuatro especies. El experimento dos probó la habilidad de *Corymbia maculata* y *Corymbia ficifolia* para penetrar suelo compactado a densidades aparentes de 1.4, 1.6 y 1.8 mg/m³ a dos niveles de humedad, 7 y 10% respectivamente. Al 7% de humedad, ambas especies fueron capaces de penetrar el suelo compactado a 1.4 y 1.6 mg/m³, pero ninguna fue capaz de hacerlo para suelos compactados a 1.8 mg/m³. Al 10% de humedad, las dos especies fueron capaces de penetrar suelo compactado a 1.4 y 1.6 mg/m³. También lo hicieron para suelo de 1.8 mg/m³. Sin embargo, con significativamente menos profundidad de penetración que para las dos densidades más bajas.