THE INFLUENCE OF WATERLOGGING ON THE ESTABLISHMENT OF FOUR AUSTRALIAN LANDSCAPE TREES

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Abstract. An experiment was conducted to test the ability of recently planted trees to grow new roots under waterlogged conditions and to recover from waterlogging. *Corymbia maculata* (spotted gum, syn. *Eucalyptus maculata*), *Lophostemon confertus* (brush box), *Platanus orientalis* (oriental plane), and *Platanus × acerifolia* (London plane) were subjected to a period of waterlogging and then to a recovery phase after waterlogging had ceased. Root length was measured at the end of both the waterlogging and recovery phases. The species were found to vary considerably in their ability to tolerate and recover from a period of waterlogging. Waterlogging suppressed root and shoot growth in all experimental species. Young spotted gum and oriental plane were able to initiate new roots under waterlogged conditions but London plane and brush box were not.

Key Words. *Corymbia maculata; Lophostemon confertus; Platanus orientalis; Platanus × acerifolia*; waterlogging; urban soils; root growth; tree establishment.

Many factors influence the success of urban trees. Among these are the tolerances of their root systems to urban soil conditions. Waterlogging in urban soils is due to soil profile characteristics leading to alterations in infiltration patterns, and poor surface and subsoil drainage. Urban trees are frequently subject to high levels of soil compaction and cycles of high and low soil strength as these compacted soils dry out and are wetted again seasonally. Restrictions of drainage in urban soils can be caused by abrupt textural changes in the profile or be due to compaction caused by the movement of heavy machinery around construction sites (Craul 1992).

In well-structured soils, a day or so of heavy rainfall and high temperatures will induce anaerobic conditions very quickly in spring and summer, when plant growth rates and microbial activity are high (Greenwood 1969). These short-term anaerobic periods may cause considerable damage to root systems. In urban soils, waterlogging and anaerobiosis may occur for extended periods (Hodge and Boswell 1993), causing severe restrictions to root growth and even plant death.

To investigate tolerances of urban tree roots to waterlogging and anaerobic conditions after planting, the effects of waterlogging on a number of species of urban trees were evaluated.

MATERIALS AND METHODS

Four common urban trees in southern Australia—spotted gum (*Corymbia maculata*, syn. *Eucalyptus maculata*), brush box (*Lophostemon confertus*), oriental plane (*Platanus orientalis*), and London plane (*Platanus × acerifolia*)—were evaluated for the effects of waterlogging on root growth following planting; the timing was designed to coincide with the typical planting season in southern Australia. Three treatments were imposed on the plants, with ten replicates of each species in each treatment.

Evergreen Species

Four-month-old tube stock of brush box and spotted gum of seedling origin was used. The containers were 120 mm (4.7 in.) deep, 50 mm (2 in.) square at the top, and 39 mm (1.5 in.) square at the bottom of the container. Seedlings were selected for the experiment on the basis of their uniformity in terms of root system development, size, and leaf morphology.

Deciduous Species

Oriental plane plants were field grown and of seedling origin. London plane plants were field grown and had been propagated as hardwood cuttings. Plants were selected on the basis of their uniformity in terms of overall size, and on the form of the root system. Both species were bare rooted.

Planting

The plants were potted into black polythene bags with the soil level brought to within 4 cm (1.6 in.) of the tops of the bags. The bags were 380 mm (15 in.) deep by 150 mm (6 in.) diameter when filled, with six drainage holes at the base. Roots of the bare-rooted deciduous species were trimmed to 120 mm (4.7 in.) depth, and laterals were also trimmed so they would fit into the bags. Thirty plants of each species were potted into bags, ten plants being placed in each of the three treatments. London plane was subjected to only two treatments due to a shortage of stock.

The plants were potted into a sandy loam soil, (1% clay, 5% silt, 23% fine sand, 68% coarse sand), pH 5.2 (1:5 water extract), and electrical conductivity of 28.5 dS/m (1:5 water extract).

Treatments

Control. In this treatment, the bags were placed in plastic crates to hold them upright. Irrigation was performed manually on alternate days and the bags drained freely.

Partially waterlogged treatment. In this treatment, the plants were held in water to one-third the height of the bag, by placing them in Styrofoam crates and maintaining the water level at this depth.

Full waterlogging treatment. In this treatment, the plants were waterlogged to above the top of the soil, by placing them in large tubs deep enough to allow the water level to be kept flush with the tops of the bags.

All plants were held in the open in the Nursery at Burnley College in Australia. The area of the experiment was open and unshaded. The experiment was run from 20 August 1994 to 24 November 1994. Mean daily maximum and minimum temperatures for Melbourne, Australia, during the months the experiment was conducted are given in Table 1.

Nine weeks after potting, four replicates of each of the three treatments were randomly chosen for harvesting. The remaining plants from the waterlogging treatments were drained and placed in plastic crates to allow drainage. These plants then entered the recovery stage of the experiment. Subsequent irrigation was manual.

Measurements were taken of plant height and stem caliper during the waterlogging and recovery phases of the experiment. Plant height was measured from above the soil line in the bags. Stem caliper was measured 75 mm (3 in.) above the base of the plants. Foliar attributes such as leaf color, chlorosis, and fall, as well as complete defoliation, also were noted.

Table 1. Mean daily maximum and minimum temperature for Melbourne (Source: Bureau of Meteorology 1993).

	Aug.	Sept.	Oct.	Nov.
Mean monthly maximum temperature (°C)	14.8	17.1	19.5	21.8
Mean daily minimum temperature (°C)	6.5	7.8	9.3	11.0

Timing of Experiments

The experiment commenced during late winter. This period was chosen because it is a time of year during which planting of trees often occurs in Melbourne, and it is a period when soil moisture is usually readily available and soil strength is low. It also is a time when periods of waterlogging can occur due to the characteristic high rainfall in spring. The total duration of the experiment was 14 weeks.

Harvesting Plants

During the experiment, two replicates were harvested to determine the impact of the treatment and recovery stage on root growth and to help estimate an appropriate time to end each stage. Using this information, the treatment stage was ended at week 9. Four replicates of each species were randomly removed from the experiment. The soil was washed from the roots, and measurements of root length and shoot dry weight were made.

Measurement of Root Growth

For the two container-grown trees, root growth was assessed at the end of the two phases of the experiment by cutting new white roots away at the point at which they emerged from the container root ball. For the deciduous species, root growth was measured by cutting away new roots from the point on the root system at which the new roots had initiated. Roots were cut into 20 to 30 mm (0.8 to 0.5 in.) lengths, and root length was measured using a Comair Rootlength Scanner (Commonwealth Aircraft Corp. Ltd., Melbourne, Australia).

The use of sandy loam made the washing of soil from the roots and their recovery relatively easy. The soil and root mass was placed over a series of sieves, the smallest of which had 2 mm (0.08 in.) square mesh. For the deciduous species, shoot dry weight measurements were made from shoot growth initiated during the experiment. For evergreen species (brush box and spotted gum), the total shoot growth was harvested at the end of each stage.

During the recovery stage, plants were removed from waterlogging treatments and allowed to grow on for another 5 weeks. At the end of the recovery stage, the remaining replicates of each species were harvested and measurements of root length and shoot dry weight were made.

RESULTS

Analysis of data for root length and shoot dry weight for all species showed that the data were not normally distributed and there was not constant variance between treatments. Data were therefore analyzed via statistical techniques for nonparametric data, analyzing medians, using Kruskall-Wallace and Mann-Whitney tests (Minitab, Inc. 1995). *P* values were calculated at the 95% confidence level, with *P* values for comparisons with a statistically significant difference being $P < 0.05$.

The experimental species (spotted gum, brush box, oriental plane, and London plane), showed considerable differences in their abilities to grow new roots under waterlogged conditions and to recover from a period of waterlogging during late winter and early spring.

Root Length

Spotted gum. There was no significant difference in root length between the treatment or recovery stages for the control (no waterlogging) or partial waterlogged treatments for spotted gum (Table 2). In the fully waterlogged treatment, root growth during the recovery stage was greater than during the treatment stage (Table 2).

During the treatment stage, there was a significant difference in root length between the control and fully waterlogged treatment but not between the control and partially waterlogged treatment (Figure 1). Between the partially and fully waterlogged treatments, there was a difference in root length. During the recovery stage, there was no difference in root length between any of the treatment combinations (Figure 2).

Brush box. There was a difference in root length between the treatment and recovery stages for all the waterlogging treatments (Table 2). During the treatment stage there was no difference in root length between the control and partially waterlogged treatments (Figure 1). There was however, a difference between the control and full waterlogging and also between the partial and full waterlogging treatments. At the end of the recovery stage, there was no difference in root length between the waterlogging treatments (Figure 2).

Oriental plane. Because oriental plane was bare rooted, it was easy to observe the origin of new root growth. Primary root growth in the fully flooded treatment was evident from the cut surfaces of the roots, the surfaces of woody roots, and also from hypertrophied lenticels spread over the woody part of the root system. Secondary root growth from the primary roots also was evident. Hypertrophied lenticels were visible along the woody lateral roots, with root primordia and new roots emerging from the intumescences.

There was a difference in root length between the treatment and recovery stages for each treatment (Table 1). During the treatment stage, there was no difference between waterlogging treatments (Figure 1). At the end of the recovery stage, there was a difference between full flooding and other treatments (Figure 2).

London plane. As with oriental plane, it was easy to observe the origin of new root growth from

Table 2. Comparisons of root length between the treatment (T) and recovery (R) phases. T = R denotes no significant difference between medians; T ≠ R denotes a significant difference between medians at *P* < 0.05.

Waterlogging treatment	Median root length (m) Spotted gum	Brush box	Oriental plane	London plane
No waterlogging (control)	59.5 T, 43.2 R T = R	30.6 T, 79.5 R T ≠ R	11.6T, 63.5T T ≠ R	14 T, 50.8 R T ≠ R
Part waterlogging	34.5 T, 103.3 R T ≠ R	21.2 T, 92.3 R T ≠ R	13.9 T, 61.3 R T ≠ R	No data
Full waterlogging	1.0 T, 49.5R T ≠ R	0.00 T, 9.6 R T ≠ R	1.4 T, 28.0 R T ≠ R	0.0 T, 22.2 R T ≠ R

the bare-rooted transplants of London plane. Primary root growth in the fully flooded treatment was evident from the cut surfaces of the roots, from the surface of the roots, and from lenticels. Lenticels were visible along the woody lateral roots, with root primordia emerging from them. Collars of hypertrophied lenticels also were visible at the junction of the stem and on the woody lateral roots, with root primordia emerging from the intumescences.

There was a difference in root length between the treatment and recovery stages for the controls and the fully flooded treatments (Table 1). During the treatment stage, there was a difference in root length between the control and the full waterlogging treatment (Figure 1). For the recovery stage, there was no difference in root length (Figure 2).

Shoot Dry Weight

Spotted gum. During the treatment stage, there was a difference in shoot dry weight between the various waterlogging treatment combinations (Figure 3). At the end of the recovery stage, there was a difference between the control and fully waterlogged treatments only (Figure 4).

Brush box. During the treatment stage, there was no difference in shoot dry weight between the control and partial waterlogging, but there was a difference between the control and full waterlogging and the partial waterlogging and full waterlogging (Figure 3). Similarly, at the end of the recovery stage, the fully waterlogged plants had significantly less shoot growth than the control and the partially waterlogged treatment (Figure 4). By the end of the experiment, partially waterlogged plants showed some chlorosis and reddening of the leaves and had shed some leaves. The fully waterlogged plants were almost totally defoliated during the treatment stage and did not initiate any new growth buds till the end of the experiment.

Oriental plane. In this species, bud burst occurred 6 weeks after the experiment began. At the end of the treatment stage, fully waterlogged plants were observed to have leaves that had less than half the area of the controls and had much reduced internode growth. These leaves also exhibited chlorosis, particularly on the leaf margins. During the treatment stage, there was no difference in shoot dry weight between the controls and the partially or fully waterlogged treatments (Figure 3). There was, however, a difference between the partially and fully waterlogged treatments. At the end of the recovery stage, there was no difference between the control and partially waterlogged treatments, but there was difference between the control and fully waterlogged treatments and the partially and fully waterlogged treatments (Figure 4).

London plane. In London plane, bud burst also occurred 6 weeks after the experiment began. Fully waterlogged plants had leaves that were less than half the size of those of the controls, and internode extension also was reduced. These leaves also exhibited

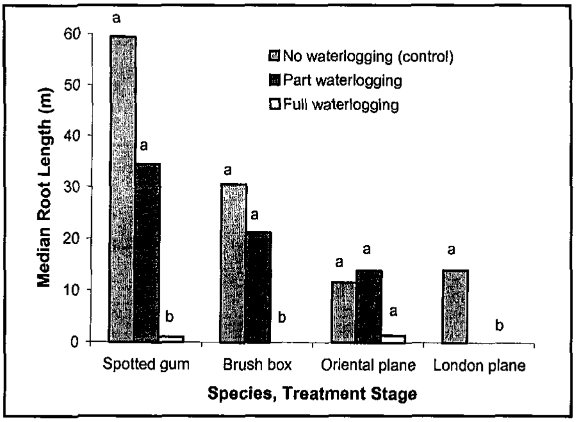

Figure 1. Root length versus treatment for spotted gum, brush box, oriental plane, and London plane (treatment phase). Differing letters between specific waterlogging treatments for each species denote significant median differences at $P < 0.05$.

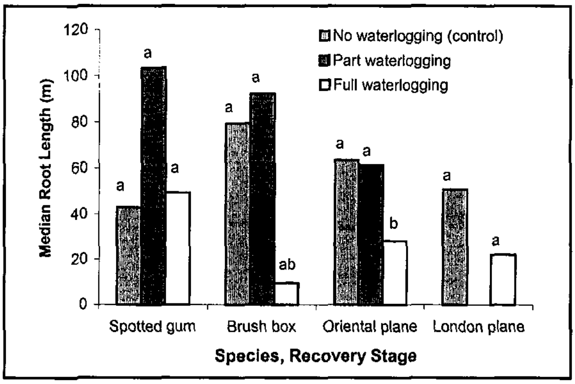

Figure 2. Root length versus treatment for spotted gum, brush box, oriental plane, and London plane (recovery phase). Differing letters between specific waterlogging treatments for each species denote significant median differences at $P < 0.05$.

chlorosis, particularly on the leaf margins. At the end of the treatment stage, there was a difference between the control and the fully waterlogged treatments (Figure 3). At the end of the recovery stage, there was no difference between the control and fully waterlogged treatments (Figure 4).

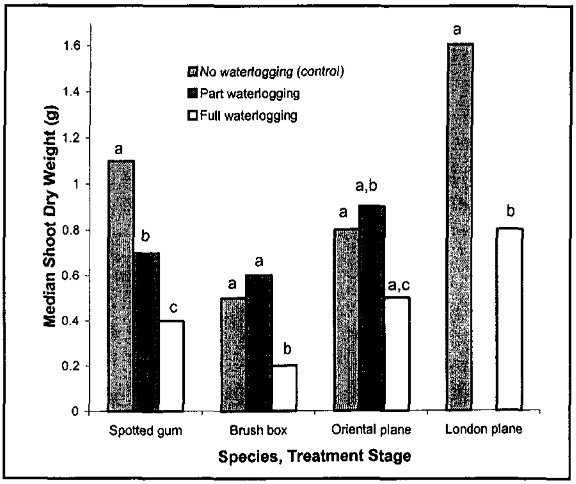

Figure 3. Shoot dry weight versus treatment for spotted gum, brush box, oriental plane, and London plane (treatment phase). Differing letters between specific waterlogging treatments for each species denote significant median differences at $P < 0.05$.

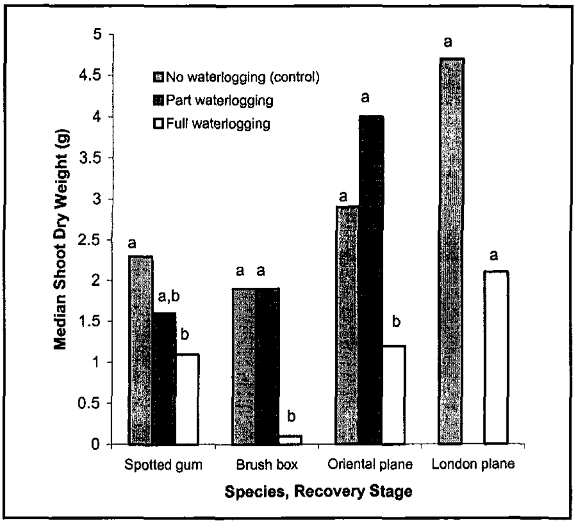

Figure 4. Shoot dry weight versus treatment for spotted gum, brush box, oriental plane, and London plane (recovery phase). Differing letters between specific waterlogging treatments for each species denote significant median differences at $P < 0.05$.

DISCUSSION

The responses to winter waterlogging of the four tree species in this experiment can be grouped into three types.

1. Spotted gum and oriental plane were able to make new root growth while waterlogged and to recover well after waterlogging ceased.
2. London plane, while unable to make new root growth while waterlogged, did produce new roots rapidly after drainage.
3. Brush box was unable to make new root growth while waterlogged and could not produce roots rapidly after draining.

These observed responses to waterlogging in different species suggest several mechanisms for tolerance of urban soil conditions.

The production of hypertrophied lenticels on the woody roots of London plane and oriental plane seedlings in this experiment suggests a mechanism whereby mature trees may initiate new root growth on woody framework roots, during waterlogging, and after drainage, when oxygen is available again. Stem hypertrophy and hypertrophied lenticels allow for movement of oxygen into the root system, usually via aerenchymatous tissue from the shoots or the stem (McKersie and Leshem 1994).

The ability to produce new roots under waterlogged conditions is another survival mechanism. Adventitious water roots may be produced on the stems of waterlogged seedlings, and soil water roots may be produced in the soil below the water line (Hook 1984). Plants in this experiment did not grow adventitious roots from hypertrophied stem lenticels formed on London plane or oriental plane.

Soil water roots are often formed after the original roots die back to secondary or primary roots, with the initiation of new roots from these points (Hook 1984). In this experiment, spotted gum demonstrated the ability to form soil water roots. However, it is not known if, or how much of, the original root system died back prior to these roots being formed. River red gum *(Eucalyptus camaldulensis)* is known to produce soil water roots, and these roots elongate rapidly as the soil begins to dry out, enhancing the survival of mature trees after flooding (Sena Gomes and Kozlowski 1980). Neither spotted gum nor brush box are riparian or floodplain species. Spotted gum is found on well-drained, sloping, and frequently rocky areas on the east coast of Australia from Queensland to Victoria (Elliot and Jones 1986). Brush box is from habitats associated with rain forest along Australia's east coast (Williams 1995).

Some plants tolerant of waterlogging can increase the oxygen supply to their roots by the modification of their root anatomy with the development of aerenchymatous tissue (Coutts and Philipson 1978b). In this study, aerenchymatous tissue was formed in hypertrophied stem tissue (usually at the base of the stem) and in individual hypertrophied lenticels on stems and roots of oriental plane, London plane, and spotted gum (Figure 5).

Adventitious water roots and soil water roots may be able to oxidize their rhizosphere, but this capacity is lost as roots harden off during dry periods. The tendency of wetland species to develop soil water roots may account for their capacity to withstand the alternating waterlogging and drying of the wetland site (Hook 1984).

Under fluctuating water table conditions, considerable death may occur in the actively growing roots of mature trees when the water table rises, but some dormant roots survive, and regrowth of soil water roots is from these (Coutts and Philipson 1978a). Soil water roots were developed on oriental plane, London plane, and spotted gum (Figure 5).

A less desirable response to waterlogging involves the death of all or most of the root system without production of new roots. The response of brush box to waterlogging in this experiment may fall into this category, since no root growth occurred during the waterlogging treatment and the plants were slow to recover once they were drained. This response has also been noted for tuliptree (*Liriodendron tulipifera)* (Hook and Brown 1973) and for Sitka spruce (Coutts and Philipson 1978a). Species that respond in this way are intolerant to waterlogging and die if waterlogged conditions persist.

Figure 5 summarizes the morphological root and shoot characteristics of the experimental species to waterlogging and attempts to rank their tolerance to waterlogging in conjunction with these characteristics.

	Brush box	Oriental plane	London plane	Spotted gum
Morphological Root Characteristics				
Developed adventitious water roots	x	x	x	x
Developed secondary roots (soil water roots)	x	✓	✓	✓
Death of most fibrous roots, no new root growth	✓	n/a	n/a	x
Developed hypertrophied lenticels on woody roots	x	✓	✓	✓
Morphological Shoot Characteristics				
Developed hypertrophied stem tissue	x	✓	✓	✓
Developed hypertrophied lenticels on stems	x	✓	✓	x
Leaf chlorosis	x	✓	✓	✓
Leaf fall[1]	✓	x	x	✓
Defoliation[2]	✓	n/a	n/a	x
Rapid root growth recovery after waterlogging	x	✓	✓	✓

RELATIVE WATERLOGGING TOLERANCE

INTOLERANT ⟵⟶ **TOLERANT**

[1] A proportion of leaves has fallen from the seedlings

[2] All leaves have fallen from the seedlings

Figure 5. Morphological root and shoot characteristics of brush box, oriental plane, London plane, and spotted gum subjected to waterlogging (✓ = possesses characteristic; x = does not possess characteristic; n/a = not applicable to dormant, bare-root transplants).

Using the relative waterlogging tolerance scale in Figure 5, spotted gum is ranked most tolerant of waterlogging because of its combined morphological root and shoot characteristics and its ability to produce rapid root growth when waterlogging was removed. Brush box is ranked as least tolerant because of its complete defoliation under waterlogged conditions, its inability to produce new root growth under waterlogged conditions, and its very slow recovery of root and shoot growth once waterlogging ceased. It was not possible to distinguish between oriental plane and London plane on the basis of morphological root and shoot characteristics.

While it is difficult to correlate these observed responses to plant performance in the landscape, the success of spotted gum and the two plane species as urban trees in southeastern Australia would seem to be consistent with the observations of this experiment. While brush box is successful as an urban tree in parks and grassed areas in streets, field observation suggests it is less able than the other species to deal with difficult sites.

Leaf fall was notable in the waterlogged treatment. The smaller amount of shoot growth for fully waterlogged spotted gum at the end of the recovery may indicate that carbohydrate was being directed into root development to compensate for root growth lost during waterlogging. Toxic compounds produced under waterlogging may have affected shoot growth, but since root growth was not affected to the same extent, this is probably not so.

CONCLUSIONS

Spotted gum and oriental plane were able to produce new root growth under waterlogged conditions and to recover rapidly after waterlogging. London plane and brush box did not grow roots under waterlogged conditions. London plane was able to recover rapidly from waterlogging and initiate new root growth. Brush box by comparison, recovered more slowly.

Shoot growth for spotted gum was not reduced by waterlogging. Under waterlogged conditions, shoot growth was reduced for brush box, London plane, and oriental plane. While shoot growth of London plane and oriental plane recovered rapidly after waterlogging ceased, as new root growth increased rapidly, brush box was unable to recover shot growth during the experiment.

Where trees are planted in sites with compacted and poorly drained soils, root response differences of the type seen in this experiment can go some way to explaining species differences in tolerance to these sites. In winter rainfall climates like southeastern Australia, tolerance of waterlogging after planting and the ability of a transplant to establish new roots after soils begin to drain will be an important survival response. In addition to tolerance to the direct effects of waterlogging, a transplant that is able to produce new roots while waterlogged, exploiting the lower soil strength of wet soil, has opportunities to explore larger soil volumes before the soil becomes too dry. Species such as brush box, which cannot grow new roots under waterlogging, are less able to exploit this opportunity and will enter the dry summer period with restricted root growth and access to smaller soil water reserves.

It is important that an understanding of soil conditions inform the design process for urban sites, particularly with regard to physical properties such as compaction, soil strength, and drainage. Species selection should reflect the known tolerances of species to critical soil conditions. As a result of this study, it is recommended that for sites where post-planting waterlogging can occur, spotted gum, oriental plane, and London plane can be considered suitable species but brush box cannot. For species less tolerant of waterlogging, subsoil drainage should be installed on sites subject to waterlogging, and will be critical for establishment success.

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Résumé. Une expérience 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* × *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 espèces ont réagi de façon considérablement différentes dans leur capacité à tolérer et à se remettre d'une période d'inondation. L'inondation à supprimé la croissance des racines et des pousses chez toutes les espèces expérimentales. Les jeunes *Corymbia maculata* et *Platanus orientalis* ont été capable d'initier de nouvelles racines sous des conditions d'inondation, contrairement au *Platanus* × *acerifolia* et au *Lophostemon confertus*.

Zusammenfassung. Es wurde ein Experiment durchgeführt, um die Fähigkeit kürzlich gepflanzter Bäume zu testen, wie sie unter wassergesättigten Bedingungen Wurzeln ausbilden können und wie sie sich von solchen Bedingungen erholen. *Corymbia maculata* (syn. *Eucalyptus maculata*), *Lophostemon confertus, Platanus orientalis* und *Platanus* × *acerifolia* wurden für einen Zeitraum diesen wassergesättigten Bedingungen und anschließend einer Erholungsphase ausgesetzt. Die Wurzeln wurden am Ende beider Phasen gemessen. Die Spezies variierten deutlich in ihrer Fähigkeit diese Bedingungen zu tolerieren und sich davon zu erholen. Die Wassersättigung unterdrückte das Wurzel- und Triebwachstum bei allen getesteten Spezies. Junge *Corymbia maculata* und *Platanus orientalis* waren in der Lage, unter gewässerten Bedingungen neue Wurzeln zu bilden, aber *Platanus* × *acerifolia* und *Lophostemon* konnten dies nicht.

Resumen. Se condujo un estudio para probar la habilidad de árboles recién plantados para producir nuevas raíces bajo condiciones de inundación y recobrarse después de la misma. *Corymbia maculata* (Syn *Eucalyptus maculata*), *Lophostemon confertus*, *Platanus orientalis* y *Platanus* × *acerifolia*, fueron sometidos a un período de inundación y a una fase de restablecimiento posterior al cese de la misma. Se midió la longitud de las raíces al final de ambos períodos. Se encontró que las especies varían considerablemente en su habilidad para tolerar y recobrarse de un período de inundación. La inundación suprimió el crecimiento de las raíces y los brotes en las ramas en todas las especies probadas. Los eucaliptos jóvenes y los Oriental plane fueron capaces de iniciar nuevas raíces bajo condiciones de inundación, pero no London plane ni *Lophostemon*.