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The effect of permeable pavements with an underlying base layer on the growth and nutrient status of urban trees

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ABSTRACT

Trees in urban areas increase the liveability of towns and cities but street tree growth can be constrained by the limited soil volume available for root growth and by reduced water and nutrient availability under impervious urban surfaces. An approach to improve the growth and health of street trees is the installation of permeable pavements. This study assessed whether permeable pavements with varying depths (0, 100 or 300 mm) of an underlying base layer affected soil moisture, soil temperature, tree growth and leaf nutrient status when broad-leaf paperbark (*Melaleuca quinquenervia*) trees were planted in two soil types, sand and clay.

Permeable pavements increased moisture levels in drier sandy soil but decreased moisture levels in wetter clay soil after rainfall, with the stabilising effect of the permeable pavement on moisture levels being related to the depth of the underlying base layer. Permeable pavements and their base layers also had moderating effects on soil temperature. Permeable pavement with a deep drainage layer (300 mm) increased trunk diameter growth by 55%, although growth was only increased when trees were planted in clay. Permeable pavements with a shallower drainage layer (0 or 100 mm) did not affect tree growth compared with trees in control asphalt pavements. However, permeable pavements without a drainage layer reduced tree height growth in clay soil by 37 to 38% compared with pavements with a 100 mm or 300 mm drainage layer. In contrast, permeable pavements without a drainage layer increased trunk diameter growth in sandy soil by 65% compared with permeable pavement with a 100 mm drainage layer. Leaf nutrient concentrations were often unaffected by pavement design but differences in growth between treatments were associated with differences in the concentrations of some nutrients including K, Mg and S. This study demonstrated that inclusion of underlying base layers is important for tree growth when permeable pavements are installed on poorly-draining soils. Inclusion of a base layer may not be optimal for tree growth when permeable pavements are installed over freely-draining soils.

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Introduction

Urban trees increase the liveability of towns and cities, providing a wide range of economic, social and environmental benefits, and enhancing the quality of life for residents. Trees in urban areas improve air quality (Tallis et al., 2011), reduce noise (Lohr et al., 2004), attenuate stormwater flow (Seitz and Escobedo, 2011), mitigate urban heat-island effects (Gago et al., 2003) and provide economic benefits through increased property prices and energy savings (Donovan and Butry, 2010; Pandit and Laband, 2010). However, urbanisation typically replaces the natural vegetated state of surfaces with impervious surfaces such as rooftops, roads, driveways and parking areas (Gill et al., 2007). This reduction of vegetated area can impose dramatic changes on a catchment by altering its natural drainage characteristics. Increasing areas of impervious surface can affect soil moisture, soil temperature and tree growth in urban catchments (Lee and Heaney, 2003; Nowak and Greenfield, 2012). Low moisture availability in the root zone under paved surfaces can present a significant challenge for urban trees to survive and grow (Halverson and Heisler, 1981; Kozlowski, 1999).

Trees planted along streets generally require more maintenance and have shorter life spans than those growing in more-natural environments (Buhler et al., 2007). The mortality and health of street trees is influenced by site characteristics and human interactions (Lawrence et al., 2012). Poor tree growth is often associated with an inadequate volume of penetrable soil for tree roots, which can limit the availability of water and nutrients (Craul, 1992). Tree roots in urban environments often compete for underground space with urban services and infrastructure, and

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insufficient rooting space is one of the main contributors to urban tree mortality (Lindsey and Bassuk, 1992).

Impervious surfaces surrounding tree pits affect street tree growth when water is restricted from infiltrating into the soil where it may be accessed by tree roots. Impervious surfaces can also cause higher daytime temperatures in the upper soil layers, which may reduce root growth and kill tree roots particularly if temperatures reach above 40 °C (Kozlowski, 1985; Ingram et al., 1989). Trees growing in parks and forests can have a 50% higher growth rate than trees growing in streets (Close et al., 1996a,b), and plants in an open lawn site can have higher growth than those in planting sites surrounded by gravel, concrete or asphalt surfaces (Mueller and Day, 2005). Trees planted in sites with larger tree pits and a smaller area of impervious surface can be taller and have a larger diameter at breast height (DBH) than trees planted at sites with increased areas of impervious surface (Close et al., 1996a,b; Grabosky and Gilman, 2004; Mueller and Day, 2005; Rahman et al., 2013).

One approach to making the soil beneath pavements more conducive to street tree growth is the use of permeable pavements (Volder et al., 2009; Morgenroth and Visser, 2011; Mullaney and Lucke, 2014). Permeable pavements may reduce the below-ground stress experienced by urban trees by allowing water to infiltrate into the sub-soil. This potentially improves growing conditions for roots and reduces water shortage and nutrient uptake issues for trees. Porous concrete pavement increased the height, DBH and root biomass of *Platanus orientalis* trees, when compared with an impervious concrete surface (Morgenroth, 2011; Morgenroth and Visser, 2011). In contrast, porous concrete pavements did not affect the DBH of *Liquidambar styraciflua* trees, when compared with impervious concrete plots (Volder et al., 2009).

Further to this, another potential approach for improving tree growth is to change the moisture profile under the permeable pavement by installing underlying base layers. These layers may improve root growth by increasing the water storage capacity of the pavement system (Lucke and Beecham, 2011; Viswanathan et al., 2011). The base layers may capture and store stormwater, allowing it to infiltrate through the underlying soil for longer periods than would have been achieved under natural conditions. Periodic drying of the base layers may also suppress shallow root growth, encouraging root growth at greater depths where moisture and temperature levels are more stable.

The objective of this study was to understand how permeable pavements with varying depths of underlying base layer would affect the growth and leaf nutrient concentrations of urban trees. Permeable pavements may alter the availability of water to roots and this was anticipated to affect the above-ground growth and leaf nutrient status of trees. A field study was established to test the hypotheses that the use of permeable pavements with varying depths of base layer would affect: (1) the moisture level and temperature of the soil; (2) the height and trunk-diameter growth of urban trees, and (3) the nutrient concentrations in leaves of urban trees. The results of this study have the potential to assist urban landscape designers, engineers and researchers of street trees in designing and installing pavement systems that improve the growth of trees planted in urban environments.

Methodology

Study site

Thirty-two pavement research plots were installed in October 2012 at the University of the Sunshine Coast, Queensland, Australia (26°43′S, 153°04′E). The study site was on the western perimeter of a car park at the university campus (Fig. 1). The site included unirrigated turf grass banking to the west, and an impermeable asphalt car park surface to the east, of the study plots. This replicated an

Fig. 1. *Melaleuca quinquenervia* trees immediately after planting in 3 m × 3 m permeable pavement plots between a car park and grass banking.

urban street environment with a road or car park on one side and grass edging or permeable garden beds on the other.

The climate of the site is subtropical with mean daily maximum temperatures ranging from 20.8 °C in July to 28.6 °C in January and mean daily minimum temperatures ranging from 9.4 °C in July to 21.3 °C in January (Bureau of Meteorology, 2014). The region has an average annual rainfall of 1737 mm (Bureau of Meteorology, 2014). Rainfall is higher during the summer and autumn months, particularly from February to April, with mean monthly rainfall of 255 mm in February, 220 mm in March and 202 mm in April.

Experimental design

Four pavement treatments were investigated, including a traditional asphaltic control pavement and three permeable-paving designs (Fig. 2). The treatments were: (1) a conventional asphaltic concrete (AC) surface; (2) permeable pavement with no base layer (PP); (3) permeable pavement with a base layer of 100-mm depth (PP-100); and (4) permeable pavement with a base layer of 300-mm depth (PP-300). Four replicates of each of the four designs were constructed in both a sandy-loam soil (‘sand’) and a clay–loam soil (‘clay’) to give a total of 32 tree plots. A 96 m long × 3 m wide × 1 m deep trench was excavated from the natural clay soil at the site. Half of the excavated clay soil was re-filled along 48 m of the trench and this was used for 16 of the 32 tree plots. Sand was filled in to the other 48 m of the trench and this was used for the other 16 tree plots. Both soils were lightly compacted using a roller. No drainage material was installed at the base of the trench, and so sub-trench drainage was through infiltration to the underlying soil.

The AC pavement was constructed in accordance with Australian standards (AS 3727–1993) and was approximately 30 mm thick. All permeable pavement treatments consisted of a layer of 80 mm thick permeable interlocking concrete pavers (PICP) set on a 30 mm thick layer of 2–5 mm diameter washed bedding aggregate. The PP-100 and PP-300 treatments were similar in design to the PP treatment except that these also included a layer of 20 mm rock screenings (‘base layer’), 100 mm and 300 mm deep, respectively (Fig. 2). The tree pit openings were 0.6 m × 0.6 m in size and were installed within the centre of a 3 m × 3 m paving plot. The paving plots were not hydraulically separated from each other, allowing roots to eventually grow beyond the paving plot. The centres of adjoining tree pits were, therefore, 3 m apart.

Thirty-two saplings of broad-leaf paperbark, *Melaleuca quinquenervia* (Myrtaceae), raised in 25 L black-plastic planter bags in a

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