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The effect of permeable pavements with an underlying base layer on the ecophysiological status of urban trees

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ABSTRACT

Impervious surfaces can adversely alter the soil conditions encountered by tree roots in urban environments. However, these conditions may be rendered more suitable for tree growth by the use of permeable surfaces. This study assessed whether permeable pavements with varying depths (0, 100 or 300 mm) of underlying base layer affected the ecophysiological status of broad-leaf paperbark (*Melaleuca quinquenervia*) trees planted in sandy or clay soils. This study measured instantaneous leaf gas exchange, including photosynthesis (A_{1400}), CO_2 concentration at the carboxylation site (C_i), stomatal conductance (g_s) and intrinsic water use efficiency (i*WUE*), and assessed soil and leaf total nitrogen (TN) concentrations. This study also determined longer-term nitrogen cycling and water use efficiency by measuring nitrogen and carbon isotope compositions ($\delta^{15}N$ and $\delta^{13}C$) of the soil and leaves. Each of these variables was then related to tree growth over the 18 months of the study. The study found that the different permeable pavement treatments often did not affect A_{1400}, C_i, g_s or iWUE, and no significant correlation was found between these four variables and tree growth during the initial tree establishment phase when growth was slow. However, tree height and DBH growth during this phase did correlate with leaf δ^{15}N in both soil types, suggesting that rapid nitrogen cycling was beneficial for initial growth. In contrast, trunk-diameter growth increments during the subsequent period of rapid growth were positively correlated with $A_{1400,}$ C_i and g_s, and negatively correlated with leaf δ^{13}C, for trees in clay soil. Trees in clay soil were prone to waterlogging. However, installation of a base layer below the permeable pavement surface was found to reduce waterlogging, decrease leaf δ^{13}C and increase tree growth. These results demonstrate that inclusion of a base layer is important for promoting tree growth when permeable pavements are installed over poorly-draining soils such as clay.

Keywords:

Street trees, *Melaleuca quinquenervia*, gas exchange, photosynthesis, nitrogen, carbon

Introduction

Global population growth has led to the rapid conversion of greenfield sites into urban areas that contain high proportions of impervious surface areas such as pavements, roads, car parks and roofs (Gill et al., 2007; Mejía and Moglen, 2010). These impervious surfaces can alter the catchment hydrology and affect the moisture, temperature, porosity and chemistry of underlying soil (Lee and Heaney, 2003; Nowak and Greenfield, 2012; Ugolini et al., 2012). Low moisture, high temperature and inadequate nutrient availability in the root zone can present significant challenges for urban tree growth (Halverson and Heisler, 1981; Kozlowski, 1985). Trees planted along streets generally require more maintenance and have shorter life spans than trees growing in more-natural environments, due to these changes in soil conditions (Buhler et al., 2007). A fundamental challenge for planners and landscapers is to design pavement surfaces that sustain the growth of trees in urban areas.

The soil beneath pavements may be rendered more suitable for tree growth by the use of permeable, rather than impermeable, pavement surfaces (Volder et al., 2009; Morgenroth and Visser, 2011; Mullaney et al., 2015a). Permeable pavements permit stormwater to pass through the pavement surface and infiltrate the soil (Mullaney and Lucke, 2014). Increased moisture levels and the influx of organic matter through the permeable pavement surface can increase the availability of nutrients to tree roots. Permeable pavements often have a higher albedo than asphaltic concrete surfaces, and this can have a moderating effect on underlying soil temperatures (Guan et al., 2011; Mullaney et al., 2015a, 2015b). The beneficial effects on soil moisture, temperature and nutrient availability provided by permeable pavements may improve growing conditions for street trees.

Permeable pavements have been shown to increase the root biomass and above-ground growth of *Platanus orientalis* trees (Morgenroth, 2011; Morgenroth and Visser, 2011). The current authors have also demonstrated recently that permeable pavements affect the soil moisture, soil temperature, above-ground growth and leaf-nutrient status of *Melaleuca quinquenervia* trees (Mullaney et al., 2015b). The effects on tree growth were found to be dependent on the soil type (sand or clay) and the depth of the base layer installed under the permeable pavement. Three different base layer depths were trialled in the study, namely 0 mm, 100 mm and 300 mm. The study found the greatest increase in tree growth occurred when the trees were planted in clay soil and the permeable pavements included a 300 mm deep base layer under the pavement surface. The differences among pavement treatments became most evident when trees entered a phase of more-rapid growth subsequent to a 12-month period of establishment in the pavement plots (Mullaney et al., 2015b).

Little is known about the ecophysiological responses of trees to the different soil conditions provided by permeable pavements. Above-ground growth of trees is linked to their photosynthetic capacity, which is, in turn, often correlated with the concentration of total nitrogen (TN) in leaves (Huang et al., 2008a, 2008b; Hosseini Bai et al., 2013, 2014a, 2014b). Nitrogen (N) availability to trees can be determined by measuring leaf TN as well as soil and leaf N-isotope composition, $\delta^{15}N$; i.e. the relative composition of the heavier and lighter isotopes, ^{15}N and ^{14}N, respectively (Ibell et al., 2013; Hosseini Bai et al., 2014a, 2014b). Microbial N turnover increases N availability in the soil. However, lighter ^{14}N compounds leach or volatilise faster than heavier ^{15}N compounds, leading to ^{15}N enrichment (Högberg, 1997). Uptake of more ^{15}N-enriched substrates from the soil results in leaf $\delta^{15}N$ enrichment. An increase in leaf $\delta^{15}N$ is, therefore, an indicator of rapid N transformation in the underlying soil (Högberg, 1997).

Water availability is also a driving factor for the photosynthetic capacity of trees (Hosseini Bai et al., 2014b). A restriction in water availability in the soil causes stomata to close in the leaves, reducing stomatal conductance (g_s) and decreasing the concentration of carbon dioxide (CO_2) at the carboxylation site in the leaf (C_i). This lowers the photosynthetic capacity of leaves and also reduces the transport of nutrients from the roots to the shoot (Hosseini Bai et al., 2014a, 2014b). When sufficient water is available to trees, enzymes in the photosynthetic pathway discriminate against the heavier molecule, $^{13}CO_2$, and preferentially use the lighter molecule, $^{12}CO_2$. However, a greater proportion of $^{13}CO_2$ is fixed in the leaves when g_s is reduced under water-limiting conditions (Farquhar and Richards, 1984). This becomes manifest as higher leaf $\delta^{13}C$ (i.e. the relative composition of ^{13}C and ^{12}C fixed in the leaves) and higher water use efficiency (WUE) in trees that are under water stress (Hosseini Bai et al., 2014a, b).

Measurements of leaf-level photosynthesis (A_{1400}), TN, intrinsic water use efficiency (i*WUE*), g_s and C_i provide an immediate picture of tree responses to N and water at a single point in time. Measurements of $\delta^{15}N$ and $\delta^{13}C$ provide a retrospective, longer-term picture of N and water use by trees (Norra et al., 2005; Huang et al., 2008a, 2008b; Hosseini Bai et al., 2014a, 2014b). In general, leaf $\delta^{15}N$ and $\delta^{13}C$ enrichment suggest rapid N cycling and water limitation, respectively.

The objective of this study was to determine how these ecophysiological variables of urban trees respond to the different soil conditions provided by permeable pavement treatments with three base layer depths (0, 100 and 300 mm). This study hypothesised that (1) permeable pavements with different depths of underlying base layer would affect the N and water relationships of trees, and (2) tree growth would be correlated with some of these ecophysiological variables. The results of the study will help engineers and landscape planners to design pavement systems that maximise urban tree growth.

Methodology

Study site and experimental design

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), as described by Mullaney et al. (2015b). The research site replicated an urban street environment with a car park on one side and grass edging on the other (Fig. 1). Daily rainfall and daily mean air temperatures for the study period were recorded by a weather station at Sunshine Coast Airport, 13 km along the same coastal plain from the study site (Fig. 2).

Four pavement treatments were investigated (Fig. 3): (1) a conventional asphaltic concrete (AC) surface used as a control; (2) permeable pavement with no base layer (PP); (3) permeable pavement with a 100-mm base layer (PP-100); and (4) permeable pavement with a 300-mm base layer (PP-300). The AC treatment was 30 mm thick and constructed in accordance with Australian Standards (AS 3727-1993). All permeable pavement treatments were constructed of permeable interlocking concrete pavers (PICP) 80 mm thick. The base layer consisted of 20 mm diameter drainage aggregate derived from basalt. Base layers were lightly compacted using a roller.

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. Soil was classified based on field texture as described in Macdonald et al. (1990). Soil moisture levels beneath each of the tree plots were reported previously (Mullaney et al., 2015b). Permeable pavements increased moisture levels in sandy soil but decreased moisture levels in wetter clay soil, when compared with asphaltic concrete surfaces, especially after rainfall events (Mullaney et al., 2015b). The stabilising effect of the permeable pavements on soil moisture levels was also related to the depth of their sub-base (Mullaney et al., 2015b). Each of the tree planting pits was 0.6 m × 0.6 m within the centre of each 3.0 m × 3.0 m paving plot. Thirty-two saplings of broad-leaf paperbark, *Melaleuca quinquenervia* (Myrtaceae), with mean (± S.E.) height of 1.88 ± 0.09 m, were randomly assigned to the plots and planted within the tree planting pits in October 2012, as described by Mullaney et al. (2015b). Trees were planted within a central soil column within each of the pavement plots. The soil was the same as that in each of the paving plots; i.e. sand or clay. Tree growth (height and DBH) was measured at intervals of 6, 12 and 18 months after planting. Growth increment (GI) measurements were reported in Mullaney et al. (2015b) and were calculated using $GI = M_L - M_O$, where M_L was the measurement at a specific time interval and M_O was the initial measurement at time of planting.

Gas exchange measurements

Gas exchange measurements were conducted on all 32 trees at 6, 12 and 18 months after planting (April 2013, October 2013 and April 2014). On each occasion, three fully expanded leaves of similar age were selected close to the tip of branches approximately halfway up the canopy on the northern side of the tree. Photosynthesis was measured using a portable photosynthesis system (Model LI-6400, LI-COR Biosciences, Lincoln, NE). Data were recorded at a constant CO_2 concentration of 380 µmol mol^{-1} and a photosynthetically active radiation (PAR) level of 1,400 µmol m^{-2} s^{-1} adjusted by blue-red light-emitting diodes (Model 6400-02B). Parameters obtained were leaf photosynthesis at 1,400 µmol m^{-2} s^{-1} PAR (A_{1400}), CO_2 concentration at the carboxylation site (C_i) and stomatal conductance (g_s). Intrinsic water use efficiency (i*WUE*) at leaf level was determined as A_{1400}/E (µmol $mmol^{-1}$), where E was the transpiration rate (Farquhar and Richards, 1984). All measurements were taken on sunny days between 08:30 am and 12:00 noon.

Leaf total N concentration, N isotope composition, and C isotope composition

The leaves used to measure gas exchange were collected and stored in separate bags before being transferred to the laboratory. Samples were oven dried at 50°C to a stable weight and then ground to a fine powder (Hosseini Bai et al., 2013) using a Rocklabs™ ring grinder (Rocklabs, Auckland, New Zealand). Approximately 4 mg of the resulting homogenised powder was transferred into an 8 × 5 mm tin capsule prior to analysis in an isotope ratio mass spectrometer (GV Isoprime, Manchester, UK). The samples were then assessed for total nitrogen concentration (TN) and N and C isotope composition ($\delta^{15}N$ and $\delta^{13}C$) as described by Prasolova et al. (2000) and Xu et al. (2003).

Equations 1 and 2 were used to estimate leaf $\delta^{15}N$ and $\delta^{13}C$, respectively:

$$\delta^{15}N = 1000 \times [(R_{\text{sample}} - R_{\text{std}})/R_{\text{std}}) \qquad \text{(Eqn. 1)}$$

where R_{sample} is the $^{15}N/^{14}N$ ratio of the sample (leaves or soil) and R_{std} is the standard $^{15}N/^{14}N$ ratio of atmospheric N_2.

$$\delta^{13}C = 1000 \times [(R_{\text{sample}} - R_{\text{std}})/R_{\text{std}}) \qquad \text{(Eqn. 2)}$$

where R_{sample} is the $^{13}C/^{12}C$ ratio of a sample (leaves or soil) and R_{std} is the $^{13}C/^{12}C$ ratio of the international PeeDee Belemnite (PDB) standard.

Soil total N concentration, N isotope composition, and C isotope composition

A soil core, 60 mm in diameter, was extracted from each plot at 12 and 18 months after tree planting, halfway between the pavement edge and the tree planting pit (i.e. 0.6 m from the edge of the tree pit). The uppermost 10 cm of soil was extracted from each core. The soil samples were sieved through a 2 mm sieve and then air-dried. The air-dried soil samples were ground and then analysed using an isotope ratio mass spectrometer to measure TN and $\delta^{15}N$ and $\delta^{13}C$. Soil N and C isotope composition ($\delta^{15}N$ and $\delta\ ^{13}C$) were calculated using Equations (1) and (2).

Statistical analysis

Data were analysed using analysis of variance (ANOVA) methods, comparing the four treatments within each soil type at each time point, using SPSS v.21 statistical software (IBM Corporation). One-way ANOVA was used because extensive treatment × soil type interactions were detected by 2-way ANOVA. Square root or log transformations were applied when variances were heterogeneous. Post-hoc least significant difference (LSD) tests were performed only when significant differences were detected by ANOVA. Pearson's product moment correlation coefficients were also calculated between each of the ecophysiological variables in this paper and the above-ground growth increments reported previously (Mullaney et al., 2015b) for the 16 trees in each of the two soil types. These growth increments (GI) were calculated:

$$GI = M_y - M_x \qquad \text{(Eqn. 3)}$$

where M_y was the measurement at a specific time point (e.g. 6, 12 or 18 months after planting) and M_x was the measurement at a previous time point (e.g. 0, 6 or 12 months after planting). This method was used to determine GI for both tree height and trunk diameter. Means are reported with standard errors, and differences or interactions were regarded as significant at $p<0.05$.

Results

Leaf gas exchange: A_{1400}, C_i, g_s *and* iWUE

Permeable pavement treatments did not significantly affect A_{1400}, C_i, g_s or i*WUE* of *M. quinquenervia* leaves at 12 or 18 months after planting in sandy soil or at 6, 12 or 18 months after planting in clay soil (Fig. 4). However, at 6 months after planting in sandy soil, trees in the PP treatment had higher A_{1400} and g_s than trees in the AC pavement (Figs 4a and 4e) and higher A_{1400}, C_i and g_s than trees in the PP-300 treatment (Figs 4a, 4c and 4e). After 6 months, trees in the PP-300 treatment in sandy soil had higher i*WUE* than trees in all other treatments (Fig. 4g).

Leaf TN, leaf $\delta^{15}N$ *and leaf* $\delta^{13}C$

Permeable pavement treatments did not significantly affect leaf TN at 6 or 12 months after planting in sand (Fig. 5a) or at 12 or 18 months after planting in clay (Fig. 5b). However, at 18 months after planting, trees in the PP-100 treatment in sand had lower leaf TN than trees in the AC or PP treatments (Fig. 5a). In contrast, at 6 months after planting in clay, trees in the PP treatment had lower leaf TN than trees in all other treatments (Fig. 5b).

The PP-100 and PP-300 treatments lowered leaf δ^{15}N at both 12 and 18 months after planting, when compared with the AC pavement in sandy soil (Fig. 5c). The PP treatment also reduced leaf δ^{15}N at 18 months after planting in sandy soil (Fig. 5c). However, in clay soil, the PP-300 treatment increased leaf δ^{15}N at 6 months after planting (Fig. 5d). Leaf δ^{15}N did not differ significantly among treatments at 12 and 18 months after planting in clay soil (Fig. 5d).

Permeable pavement treatments did not significantly affect leaf $\delta^{13}C$ at any time during the study in sandy soil (Fig. 5e) or clay soil (Fig. 5f). However, trees in the PP-300 treatment had lower leaf $\delta^{13}C$ (-30.0 ± 0.2‰) at 18 months after planting than trees in the PP treatment (-28.0 ± 0.3‰) above clay soil (Fig. 5f).

Soil TN, soil $\delta^{15}N$ and soil $\delta^{13}C$

Sandy soil under the permeable pavement treatments had lower TN than sandy soil under the AC pavement at 12 months after planting (Fig. 6a). Soil TN did not differ significantly between treatments at 18 months after planting in sand (Fig. 6a), or at 12 and 18 months after planting in clay (Fig. 6b).

The soil under the permeable pavement treatments often had lower $\delta^{15}N$ than soil under AC control pavement. Compared with the AC pavement, soil $\delta^{15}N$ was reduced under the PP pavement after 12 months in sand (Fig. 6c). Soil $\delta^{15}N$ was also reduced under the PP, PP-100 and PP-300 pavements after 18 months in sand (Fig. 6c), and under the PP and PP-300 pavements after 18 months in clay, compared with the AC pavement (Fig. 6d). Permeable pavements did not affect soil $\delta^{13}C$ at either 12 or 18 months after planting in sand (Fig. 6e) or clay (Fig. 6f).

Relationships between ecophysiological parameters and tree growth

The relationships between the ecophysiological parameters and tree growth differed markedly between the first 12 months and the subsequent measurements at 18 months after planting (Table 1). Tree growth during the first 12 months after planting was not correlated with A_{1400}, C_i, g_s, i*WUE* or leaf $\delta^{13}C$. However, tree height increments from 0–6 months and

0–12 months in both sand and clay soils showed a positive correlation with leaf δ^{15}N at 6 and 12 months after planting, respectively. Trunk-diameter increment from 0–6 months in clay soil showed a positive correlation with leaf δ^{15}N at 6 months after planting. Trunk-diameter increment from 0–6 months and height increment from 0–12 months in clay soil also showed a positive correlation with leaf TN at 6 and 12 months after planting, respectively. Height increment from 0–12 months in sandy soil showed a positive correlation with soil δ^{13}C at 12 months after planting.

In contrast, trunk-diameter increments from 0–18 months and 12–18 months in clay soil showed a positive correlation with C_{i}, g_s and soil δ^{15}N, and a negative correlation with leaf δ^{13}C, at 18 months after planting (Table 1). Trunk-diameter increment from 0–18 months in clay soil was correlated positively with A_{1400} at 18 months after planting. Trunk-diameter increment from 0–18 months in sandy soil was correlated with leaf TN at 18 months after planting. However, tree height and trunk-diameter increments from 0–18 months and 12–18 months after planting in either soil type were not correlated with leaf δ^{15}N at 18 months after planting.

Discussion

Permeable pavements with underlying base layers can alter the moisture content of urban soils and affect the growth of urban trees (Mullaney et al., 2015b). However, little was known about how urban trees respond physiologically to the different soil conditions provided by permeable pavements. This study found that permeable pavement treatments often had no effect on the leaf gas-exchange and water-use variables, $A_{1400,}$ C_{i}, g_s, i*WUE* and leaf δ^{13}C, of *Melaleuca quinquenervia* trees on individual days. In addition, these variables had no significant correlation with tree growth during the first 12 months after planting.

Tree growth did not differ greatly among the pavement treatments during the first 12 months after planting. However, PP treatments were found to promote greater trunk-diameter growth in sandy soil than the PP-100 and PP-300 treatments (Mullaney et al., 2015b). The particularly low levels of leaf δ^{15}N, indicative of lower soil-nitrogen transformation, help to explain the poor initial growth of PP-100 trees in sand. Permeable pavement treatments often reduced δ^{15}N in the underlying soil, particularly in the freely draining sandy soil. Reduced soil δ^{15}N suggests less microbial cycling of soil N (Högberg, 1997), and this may affect root establishment and tree growth (Ibell et al., 2013). Indeed, another N-cycling variable, leaf δ^{15}N, was correlated with tree growth during the first 12 months after planting in both of the soil types, and leaf TN was also correlated with tree growth during this period in clay soil. This indicates that N cycling, and leaf TN of trees planted in clay soils, are important determinants of initial growth during tree establishment in urban pavement plots.

A different set of relationships emerged between the ecophysiological variables and tree growth after the initial 12 months after planting. At 18 months after planting, leaf δ^{15}N was no longer correlated with tree growth. However, trunk-diameter growth of trees in clay soil was correlated positively with the gas-exchange and water-use variables, $A_{1400,}$ C_{i} and g_s, and correlated negatively with leaf δ^{13}C. The major differences in tree growth among pavement treatments occurred after the initial 12 months, when tree growth became much more rapid. These growth differences were particularly evident in the trunk diameter of trees planted in clay soil (Mullaney et al., 2015b). The clay soil became heavily saturated after several rainfall events between 12 and 18 months after planting. However, the PP-300 treatment moderated soil moisture levels, increased sulphur uptake into leaves (an indication of more-optimal soil moisture), and greatly increased trunk-diameter growth (Mullaney et al., 2015b).

Waterlogging of poorly-draining soil can displace air from soil pockets, causing anoxia of the roots (Akhtar and Nazir, 2013; Pimentel et al., 2014) and leading to the closure of stomata in the leaves (Lewty, 1990; Rodríguez et al., 2011; Du et al., 2012). No significant differences in g_s, A_{1400} and C_i were found at 18 months after planting. However, these results only represented plant water relationships on a single sunny day, when the soil was not saturated. However, the retrospective picture provided by leaf δ^{13}C measurements indicated that *Melaleuca quinquenervia* trees planted within PP-300 treatments over clay soil had periods of higher g_s leading up to 18 months after planting than trees planted within PP treatments. These results support the conclusions of Mullaney et al. (2015b) that the installation of base layers is required to prevent waterlogging and sustain tree growth when permeable pavements are installed over poorly-draining soils.

Conclusions

This study investigated how ecophysiological variables of urban trees responded to the different soil conditions produced by three permeable pavement treatments with varying base layer depths (0, 100 and 300 mm). The study found that the pavement treatments sometimes affected the N and water relations of *Melaleuca quinquenervia* trees, and that tree growth was sometimes correlated with A_{1400}, C_i, g_s, leaf TN, leaf δ^{15}N, soil δ^{15}N, leaf δ^{13}C or soil δ^{13}C. However, the relationships between tree growth and these ecophysiological variables differed between the tree establishment phase when growth was slow (up to 12 months after planting) and the subsequent period of more-rapid tree growth (between 12 and 18 months after planting). The correlation between leaf δ^{15}N and tree growth during the first 12 months after planting indicates that nitrogen cycling was an important determinant of growth during tree establishment. No positive correlation was found between tree growth and leaf δ^{15}N at 18 months after planting. However, A_{1400}, C_i and g_s were positively correlated, and leaf δ^{13}C was negatively correlated, with tree growth during this rapid-growth phase. Higher leaf δ^{13}C, and lower growth (Mullaney et al., 2015b), were associated with periods of waterlogging in clay soil, particularly in treatments without a deep base layer. The results of this study support the findings of the study by Mullaney et al (2015b) that the inclusion of base layers was required to prevent waterlogging and sustain tree growth when permeable pavements were installed over poorly-draining soils. The outcomes of this study will assist urban landscape designers and engineers to identify a pavement design that encourages tree growth in specific environments.

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References

Akhtar, I., Nazir, N. 2013. Effect of waterlogging and drought stress in plants. Int. J. Water Resourc. Env. Sci. 2, 34–40.

Buhler, U., Kristoffersen, P., Larsen, S.U., 2007. Growth of street trees in Copenhagen with emphasis on the effect of different establishment concepts. Arboric. Urban For. 33, 330–337.

Bureau of Meteorology, 2014. Summary Statistics Sunshine Coast Airport - Station Number 040861. Retrieved April 1st, 2014 from http://www.bom.gov.au/jsp/ncc/cdio/weatherData/av?p_nccObsCode=136&p_display_type=dailyDataFile&p_startYear=&p_c=&p_stn_num=040861.

Du, K., Xu, L., Wu, H., Tu, B., Zheng, B., 2012. Ecophysiological and morphological adaption to soil flooding of two poplar clones differing in flood-tolerance. Flora 207, 96–106.

Farquhar, G.D., Richards, R.A., 1984. Isotopic composition of plant carbon correlates with water use efficiency in wheat genotypes. Aust. J. Plant Physiol. 11, 539–552.

Gill, S.E., Handley, J.F., Ennos, A.R., Pauleit, S., 2007. Adapting cities for climate change: the role of the green infrastructure. Built Env. 33, 115–133.

Guan, K.K., 2011. Surface and ambient air temperatures associated with different ground material: a case study at the University of California, Berkeley, Spring 2011. Retrieved June 3rd, 2014 from http://nature.berkeley.edu/classes/es196/projects/2011final/GuanK_2011.pdf.

Halverson, H.G., Heisler, G.M., 1981. Soil temperatures under urban trees and asphalt. Northeast Forest Expansion Station, Broomhall, PA. USDA Forest Service Research Paper, NE-481.

Högberg, P., 1997. ^{15}N natural abundance in soil–plant systems. New Phytol. 137, 179–203.

Hosseini Bai, S., Sun, F., Xu, Z., Blumfield, T.J., 2013. Ecophysiological status of different growth stage of understorey *Acacia leiocalyx* and *Acacia disparrima* in an Australian dry sclerophyll forest subjected to prescribed burning. J. Soils Sediments 13, 1378–1385.

Hosseini Bai, S., Blumfield, T.J., Xu, Z., 2014a. Survival, growth and physiological status of *Acacia disparrima* and *Eucalyptus crebra* seedlings with respect to site management practices in Central Queensland, Australia. Eur. J. For. Res. 133, 165–175.

Hosseini Bai, S., Blumfield, T.J., Xu, Z., 2014b. Physiological traits of *Acacia concurrens* and *Eucalyptus crebra* with respect to radical site preparation practices in a revegetation trial, south east Queensland, Australia. J. Soils Sediments 14, 1107–1115

Huang, Z., Xu, Z., Blumfield, T.J., Bubb, K., 2008a. Effects of mulching on growth, foliar photosynthetic nitrogen and water-use efficiency of hardwood plantations in subtropical Australia. For. Ecol. Manag. 255, 3447–3454.

Huang, Z, Q., Xu, Z.H., Blumfield, T.J., Bubb, K., 2008b. Variations in relative stomatal and biochemical limitations to photosynthesis in a young blackbutt (*Eucalyptus pilularis*) plantation subjected to different weed control regimes. Tree Physiol. 28, 997–1005.

Ibell, P.J., Xu, Z., Blumfield, T.J., 2013. The influence of weed control on foliar δ^{15}N, δ^{13}C and tree growth in an 8 year-old exotic pine plantation of subtropical Australia. Plant Soil 369, 199–217.

Kozlowski, T.T., 1985. Tree growth in response to environmental stresses. J. Arboric. 11, 97–111.

Lee, J.G., Heaney, J.P., 2003. Estimation of urban imperviousness and its impacts on storm water systems. J. Water Resour. Plan. Manag. 129, 419–426.

Lewty, M.T., 1990. Effects of waterlogging on the growth and water relations of three *Pinus* taxa. For. Ecol. Manag. 30, 189–201.

Mejía, A.I., Moglen, G.E., 2010. Spatial distribution of imperviousness and the space time variability of rainfall, runoff generation and routing. Water Resour. Res. 46, 1–14.

Macdonald, R.C., Isbell, R.E., Speight, J.E., Walker, J., Hopkins, M.S., 1990. Australian Soil and Land Survey Field Handbook. 2nd Edition, CSIRO, Australia.

Morgenroth, J.M., 2011. Root growth response of *Platanus orientalis* to porous pavements. Arboric. Urban For. 37, 45–50.

Morgenroth, J., Visser, R., 2011. Aboveground growth response of *Platanus orientalis* to porous pavements. Arboric. Urban For. 37, 1–5.

Mullaney, J., Lucke, T., 2014. Practical review of pervious pavement designs. Clean – Soil, Air, Water 42, 111–124.

Mullaney, J., Lucke, T., Trueman, S.J., 2015a. A review of benefits and challenges in growing street trees in paved urban environments. Landsc. Urban Plan. 134, 157–166.

Mullaney, J., Lucke, T., Trueman, S.J., 2015b. The effect of permeable pavements with an underlying base layer on the growth and nutrient status of urban trees. Urban For. Urban Green. 14, 19–29.

Norra, S., Hadley, L.L., Berner, Z., Stüben, D., 2005. ^{13}C and ^{15}N natural abundances of urban soils and herbaceous vegetation in Karlsruhe, Germany. Eur. J. Soil Sci. 56, 607–620.

Nowak, D.J., Greenfield, E.J., 2012. Tree and impervious cover change in U.S cities. Urban For. Urban Green. 11, 21–30.

Pimentel, P., Almada, R.D., Salvatierra, A., Toro, G., Arismendi, M.J., Pino, M.T., Sagredo, B., Pinto, M., 2014. Physiological and morphological responses of *Prunus* species with different degree of tolerance to long-term root anoxia. Sci. Hortic. 180, 14–23.

Prasolova, N.V., Xu, Z.H., Farquhar, G.D., Saffigna, P.G., Dieters, M.J., 2000. Variation in canopy δ^{13}C of 8-year-old hoop pine families (*Araucaria cunninghamii*) in relation to canopy nitrogen concentration and tree growth in subtropical Australia. Tree Physiol. 20, 1049–1055.

Rodríguez-Gamir, J., Ancillo, G., González-Mas, M.C., Primo-Millo, E., Iglesias, D.J., Forner-Giner, M.A., 2011. Root signalling and modulation of stomatal closure in flooded citrus seedlings. Plant Physiol. Biochem. 49, 636–645.

Ugolini, F., Bussotti, F., Lanini, G.M., Raschi, A., Tani, C., Tognetti, R., 2012. Leaf gas exchanges and photosystem efficiency of the holm oak in urban green areas of Florence, Italy. Urban For. Urban Green. 11, 313–319.

Volder, A., Watson, W.T., Viswanathan, B., 2009. Potential use of pervious concrete for maintaining existing mature trees during and after urban development. Urban For. Urban Green. 8, 249–256.

Xu, Z.H., Prasolova, N.V., Lundkvist, K., Beadle, C., Leaman, T., 2003. Genetic variation in branchlet carbon and nitrogen isotope composition and nutrient concentration of 11-year-old hoop pine families in relation to tree growth in subtropical Australia. For. Ecol. Manag. 186, 359–371.

Fig. 1. *Melaleuca quinquenervia* trees at 18 months after planting in 3 m × 3 m permeable pavement plots between an impermeable asphalt car park and turf grass banking.

Fig. 2. Daily rainfall and mean maximum air temperature at 13 km from the study site (Bureau of Meteorology, 2014).

Fig. 3. Design of the four pavement treatments: (1) a conventional asphaltic concrete surface (AC); (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). The depths of base layer and structural materials are shown.

Fig. 4. Leaf photosynthesis (A_{1400}) (a, b), CO_2 concentration at the carboxylation site (C_i) (c, d), stomatal conductance (g_s) (e, f) and intrinsic water use efficiency (i*WUE*) (g, h) of *Melaleuca quinquenervia* trees planted in sand or clay under one of four different pavement types (AC, PP, PP-100 or PP-300). Means (+S.E.) with different letters at the same time point within a soil type are significantly different (ANOVA and LSD test, $p<0.05$, $n=4$).

Fig. 5. Leaf total nitrogen (TN) concentration (a, b), nitrogen isotope composition ($\delta^{15}N$) (c, d) and carbon isotope composition ($\delta^{13}C$) (e, f) of *Melaleuca quinquenervia* trees planted in sand or clay under one of four different pavement types (AC, PP, PP-100 or PP-300). Means (+S.E.) with different letters at the same time point within a soil type are significantly different (ANOVA and LSD test, $p<0.05$, n=4).

Fig 6. Soil total nitrogen (TN) concentration (a, b), nitrogen isotope composition (δ^{15}N) (c, d) and carbon isotope composition (δ^{13}C) (e, f) of *Melaleuca quinquenervia* trees planted in sand or clay under one of four different pavement types (AC, PP, PP-100 or PP-300). Means (+S.E.) with different letters at the same time point within a soil type are significantly different (ANOVA and LSD test, $p<0.05$, n=4).

Table 1. Correlation coefficients between ecophysiological parameters and above-ground growth (height increment or trunk diameter at breast height (DBH) increment) of *Melaleuca quinquenervia* trees in pavements installed over sand or clay soil.

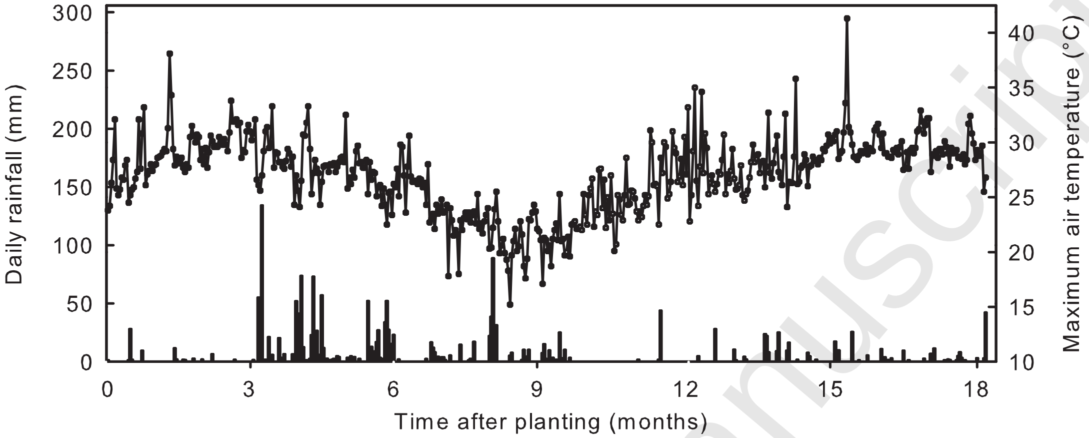
Table 2. Correlation coefficients between ecophysiological parameters and above-ground growth [height increment or trunk diameter at breast height (DBH) increment) of *Melaleuca quinquenervia* trees in pavements installed over sand or clay soil.

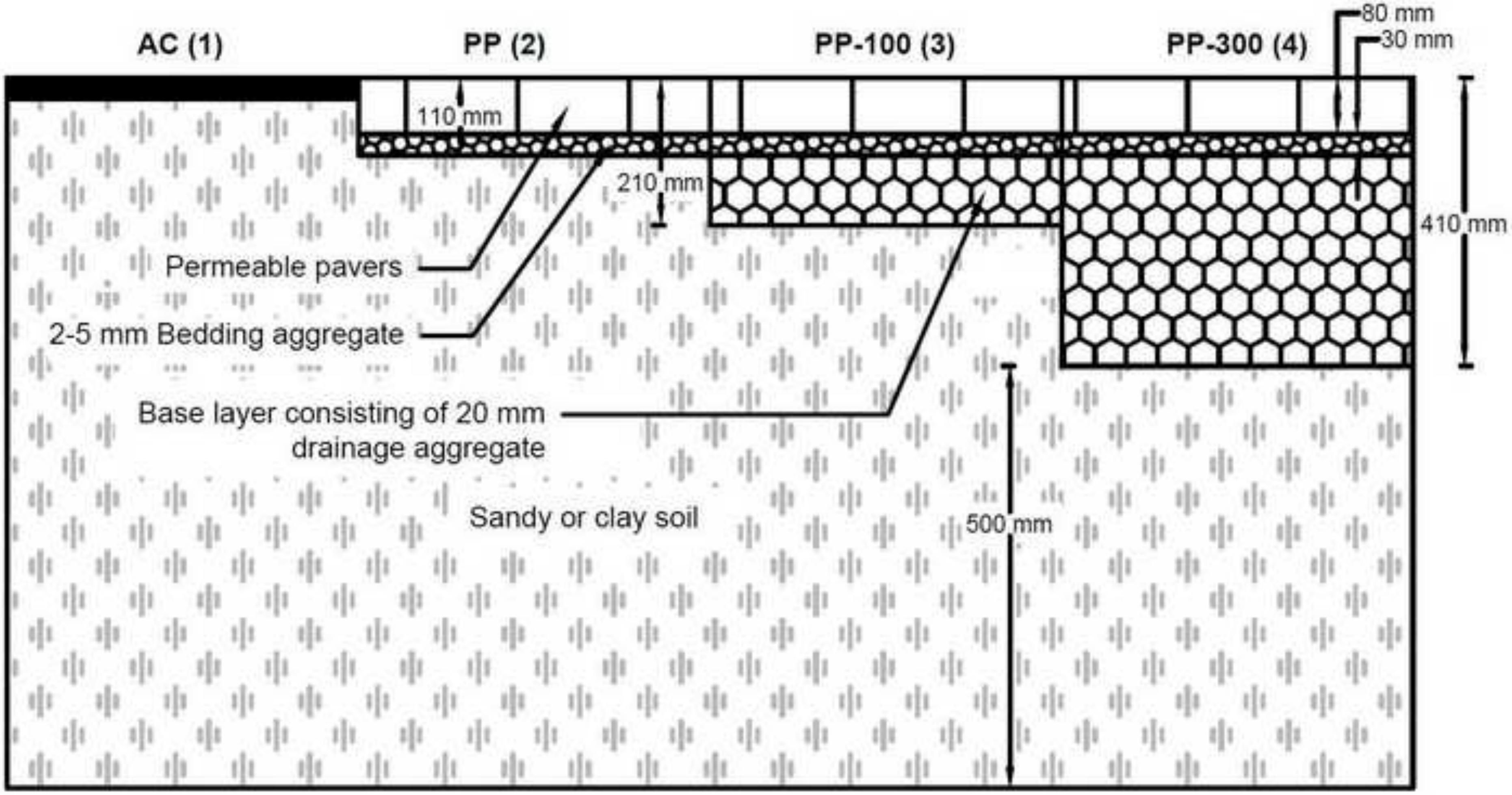
Parameter	Measurement time									
	6 months		12 months		18 months		12 months		18 months	
	Δ height 0-6 mths	Δ DBH 0-6 mths	Δ height 0-12 mths	Δ DBH 0-12 mths	Δ height 0-18 mths	Δ DBH 0-18 mths	Δ height 6-12 mths	Δ DBH 6-12 mths	Δ height 12-18 mths	Δ DBH 12-18 mths
Sand										
A_{1400}	-0.453	0.305	0.366	0.329	0.240	0.325	0.113	0.140	0.386	0.484
C_i	-0.430	0.375	0.458	0.166	0.087	-0.175	0.422	0.190	0.177	0.082
g_s	-0.393	0.365	0.439	0.287	0.247	0.121	0.254	0.045	0.383	0.348
i*WUE*	0.336	-0.235	0.062	-0.207	-0.187	0.289	-0.080	-0.028	-0.213	0.224
Leaf TN	0.429	-0.007	0.064	-0.058	0.425	**0.532***	-0.449	0.287	0.157	0.438
Leaf δ^{15}N	**0.513***	0.273	**0.511***	0.086	0.140	-0.219	-0.053	0.001	-0.028	-0.224
Leaf δ^{13}C	-0.198	0.097	-0.311	-0.134	-0.026	0.220	-0.253	-0.131	0.135	0.155
Soil TN	n/a	n/a	0.293	0.282	0.231	-0.100	0.395	-0.100	0.026	0.130

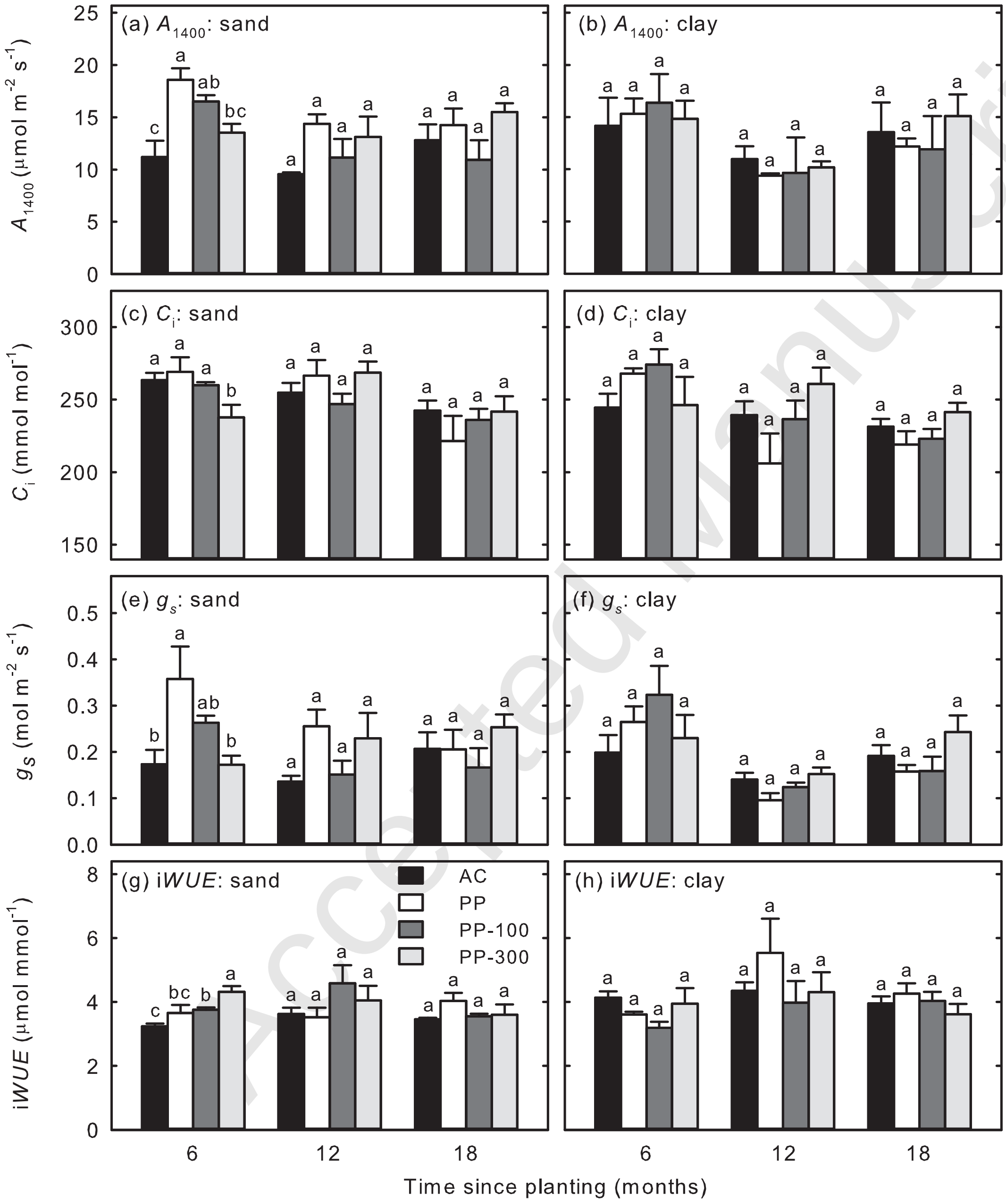
Soil δ^{15}N	n/a	n/a	0.006	-0.143	0.489	0.111	-0.300	0.076	0.457	0.195
Soil δ^{13}C	n/a	n/a	**0.542***	0.094	0.360	0.081	0.469	-0.112	0.436	0.047
Clay										
A_{1400}	0.055	-0.375	-0.104	-0.409	0.150	**0.549***	-0.039	-0.388	0.063	0.354
C_i	0.036	-0.255	0.434	0.194	0.305	**0.631***	-0.298	0.171	0.126	**0.562***
g_s	-0.057	-0.269	0.359	-0.019	0.220	**0.715***	-0.243	-0.016	0.112	**0.508***
i*WUE*	-0.203	0.039	-0.307	-0.368	-0.328	-0.454	0.007	-0.133	-0.179	-0.492
Leaf TN	0.440	**0.501***	**0.549***	0.348	0.377	0.008	-0.068	0.070	0.227	-0.112
Leaf δ^{15}N	**0.509***	**0.650***	**0.533***	0.413	0.315	0.060	0.226	-0.103	0.114	-0.175
Leaf δ^{13}C	-0.295	-0.213	-0.265	-0.416	-0.203	**-0.708***	-0.203	0.026	0.074	**-0.529***
Soil TN	n/a	n/a	0.011	0.019	0.219	0.225	0.039	-0.467	0.232	0.202
Soil δ^{15}N	n/a	n/a	0.025	-0.240	0.390	**0.580***	0.334	-0.255	0.397	**0.637***
Soil δ^{13}C	n/a	n/a	-0.270	0.335	-0.176	-0.176	-0.048	0.323	-0.140	0.285

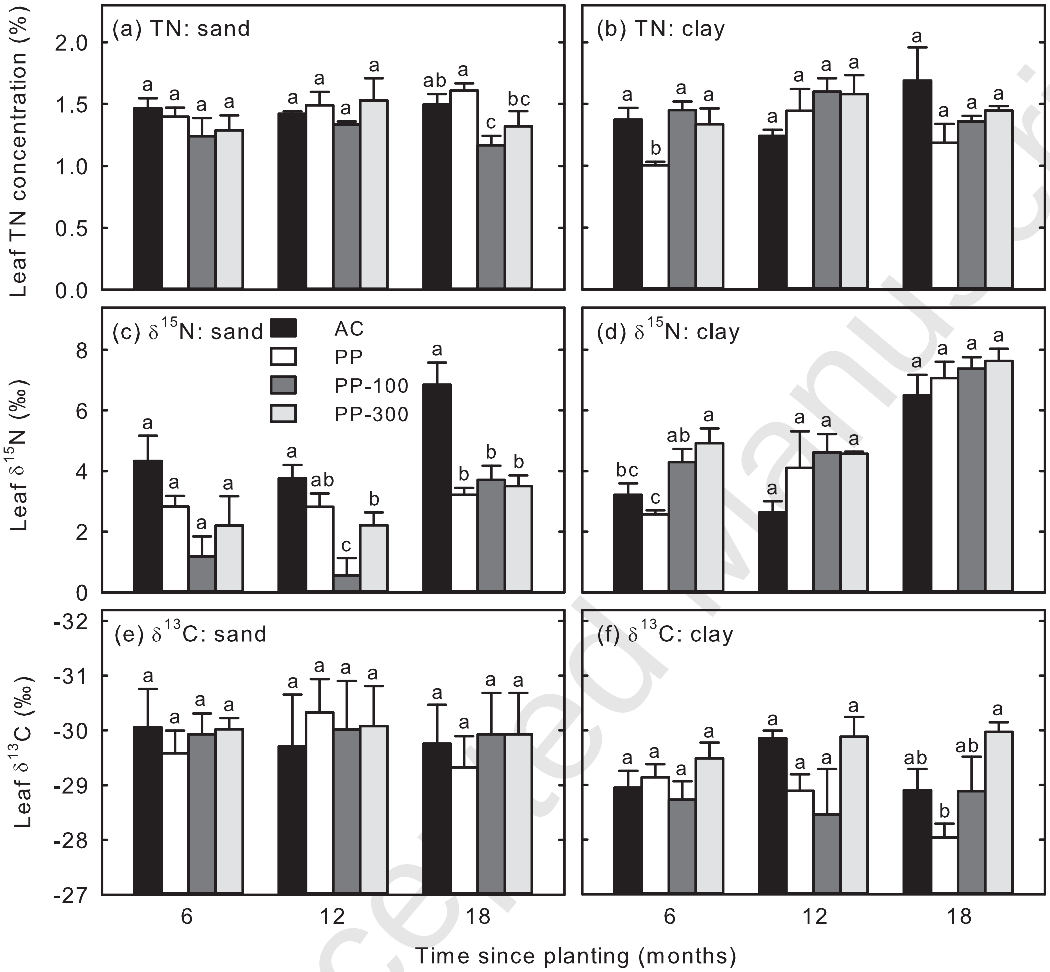
Correlations indicated in bold font with an asterisk (*) are significant (Pearson’s product moment correlation; $p<0.05$; n=16).

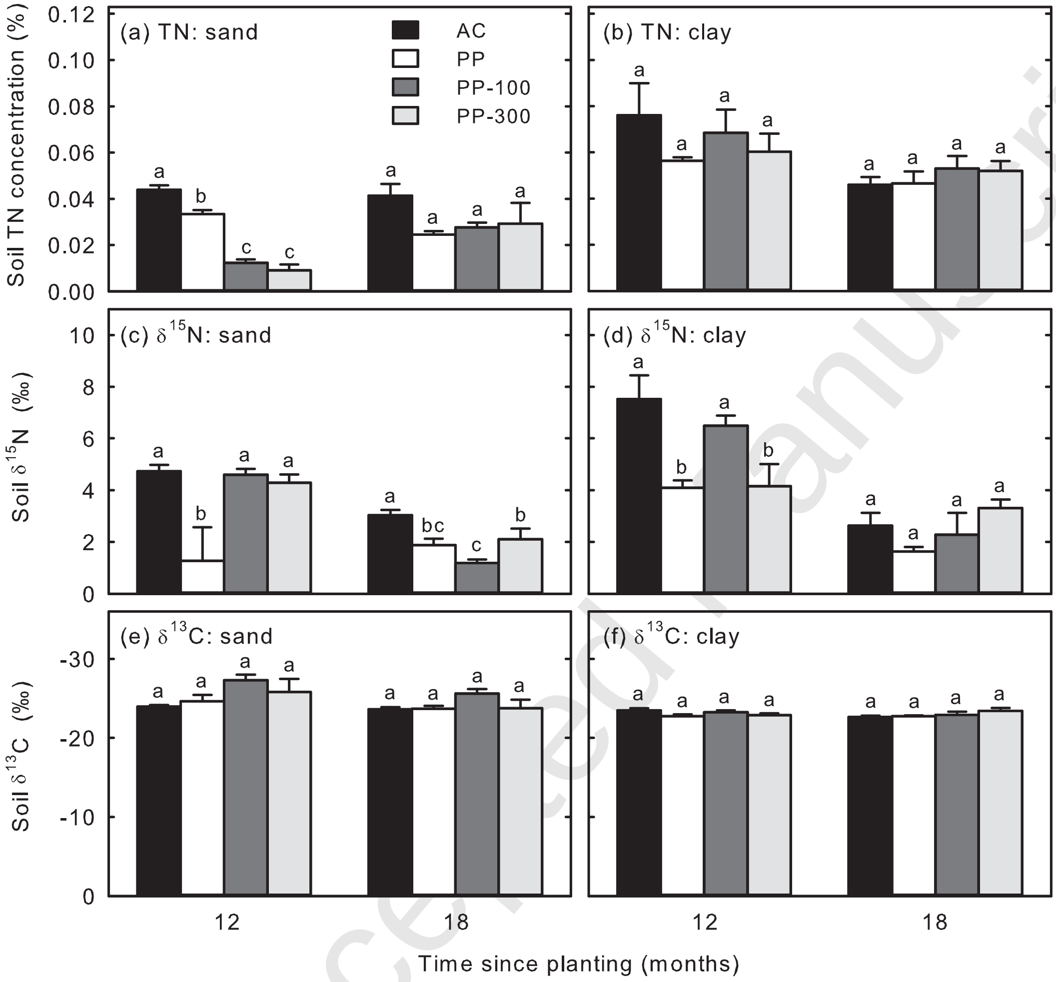
Figure


Daily rainfall (mm)
300
250
200
150
100
50
0
0
3
6
9
12
15
18
Time after planting (months)
Maximum air temperature (°C)
40
35
30
25
20
15
10


AC (1)
PP (2)
PP-100 (3)
PP-300 (4)
80 mm
30 mm
110 mm
210 mm
410 mm
500 mm
Permeable pavers
2-5 mm Bedding aggregate
Base layer consisting of 20 mm drainage aggregate
Sandy or clay soil


(a) A_{1400}: sand
(b) A_{1400}: clay
A_{1400} (μmol m^{-2} s^{-1})
0
5
10
15
20
25
c a ab bc
a a a a
a a a a
a a a a
a a a a
a a a a
(c) C_i: sand
(d) C_i: clay
C_i (mmol mol^{-1})
150
200
250
300
a a a b
a a a a
a a a a
a a a a
a a a a
a a a a
(e) g_s: sand
(f) g_s: clay
g_S (mol m^{-2} s^{-1})
0.0
0.1
0.2
0.3
0.4
0.5
b a ab b
a a a a
a a a a
a a a a
a a a a
a a a a
(g) i*WUE*: sand
(h) i*WUE*: clay
i*WUE* (μmol mmol^{-1})
0
2
4
6
8
■ AC
□ PP
▨ PP-100
▨ PP-300
c bc b a
a a a a
a a a a
a a a a
a a a a
a a a a
6
12
18
6
12
18
Time since planting (months)


(a) TN: sand
(b) TN: clay
Leaf TN concentration (%)
0.0
0.5
1.0
1.5
2.0
a a a a
a a a a
ab a c bc
a b a a
a a a a
a a a a
(c) δ15N: sand
(d) δ15N: clay
AC
PP
PP-100
PP-300
Leaf δ15N (‰)
0
2
4
6
8
a a a a
a ab c b
a b b b
bc c ab a
a a a a
a a a a
(e) δ13C: sand
(f) δ13C: clay
Leaf δ13C (‰)
-27
-28
-29
-30
-31
-32
a a a a
a a a a
a a a a
a a a a
a a a a
ab b ab a
6
12
18
6
12
18
Time since planting (months)


Soil TN concentration (%)
0.12
0.10
0.08
0.06
0.04
0.02
0.00
(a) TN: sand
(b) TN: clay
AC
PP
PP-100
PP-300
a
b
c
c
a
a
a
a
a
a
a
a
a
a
a
a
Soil δ^{15}N (‰)
10
8
6
4
2
0
(c) δ^{15}N: sand
(d) δ^{15}N: clay
a
b
a
a
a
bc
c
b
a
b
a
b
a
a
a
a
Soil δ^{13}C (‰)
-30
-20
-10
0
(e) δ^{13}C: sand
(f) δ^{13}C: clay
a
a
a
a
a
a
a
a
a
a
a
a
a
a
a
a
12
18
12
18
Time since planting (months)

- The relationships between tree growth and the ecophysiological variable differed between the first 12 months after planting and months 12-18.
- Correlation between leaf $\delta^{15}N$ and tree growth during the first 12 months indicated nitrogen cycling is an important determinant of growth during establishment.
- Higher leaf $\delta^{13}C$ related to lower tree growth and was associates with periods of waterlogging in clay soil, particularly in treatments without a base layer.
- The findings within this study support those of an early study.
- Appropriately design permeable pavements can improve the growth and health of street trees.