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Belowground effects of porous pavements—Soil moisture and chemical properties

Justin Morgenroth[a,*], Graeme Buchan[b], Bryant C. Scharenbroch[c]

[a] New Zealand School of Forestry, University of Canterbury, Private Bag 4800, Christchurch 8140, New Zealand
[b] Faculty of Agriculture and Life Sciences, Lincoln University, New Zealand
[c] Research Department, The Morton Arboretum, 4100 Illinois Route 53, Lisle, IL 60532, USA

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ABSTRACT

Impermeable pavements cover a considerable land area in cities. Their effect on the hydrological cycle is clear; as a barrier in the soil–atmosphere continuum they minimise rainfall infiltration and evaporation. Porous pavements are beginning to replace impermeable alternatives because of perceived hydrologic benefits. The impact of porous pavements on soil moisture and chemistry as they relate to urban vegetation was investigated in Christchurch, New Zealand. An experiment was established comprising 25 plots evenly distributed amongst controls (no pavement, exposed soil) and four different pavement treatments: a factorial combination of pavement type (porous, impervious) and pavement profile design (including or excluding a greywacke gravel base). Results indicate that pavements altered soil pH from moderately acidic (pH = 5.75) to more neutral levels (pH = 6.3). The effect on pH was greater beneath porous pavements, and also when a gravel base was included. Concentration of soil Al, Fe, and Mg decreased, while Na increased beneath pavements. Soil moisture was consistently higher beneath pavements than control plots, except following periods of heavy rainfall where high soil moisture muted all treatment effects. Throughout most of the study period, soil moisture content was lower beneath pavement profiles designed with the gravel base, presumably due to the gravel acting as a capillary break to a distillation process, whereby soil moisture migrates upwards to the soil surface. In early autumn, when soil moisture content was lowest for all treatments, precipitation recharged soil moisture in control plots and beneath porous pavements. But impervious pavements prevented infiltration resulting in significantly lower soil moisture content beneath these pavements. Pavements can alter soil moisture and chemical characteristics, but the effects differ depending on pavement porosity and profile design. Implications of the results pertain to stress physiology of urban vegetation, in particular drought stress avoidance.

1. Introduction

Soil physical and chemical conditions are critical for plant growth, determining the availability of water and nutrients. Despite anthropogenic disturbance, highly modified urban soils support extensive and diverse plant life, including trees. Of the anthropogenic artefacts, one of the most pervasive are impervious pavements, which are known to modify physical and chemical properties of soil including moisture content (Wagar and Franklin, 1994), temperature (Celestian and Martin, 2004), and pH (Messenger, 1986). By doing so, pavements impact the growth and survival of urban vegetation. Though the vast majority of pavements are impervious, porous pavements (also known as permeable, pervious, or no-fines pavements) have been installed more frequently for stormwater management or as a skid-resistant surface course (Ferguson, 2005). The literature supports increased infiltration (Bean et al., 2007) and evaporation (Starke et al., 2010) rates for porous pavements, so we know that urban hydrology is altered. But the literature fails to address how porous pavements affect soil characteristics that influence plant growth, like water content, pH, and nutrient concentrations. Are these soil conditions modified by porous pavements, and moreover can porous pavements affect adjacent vegetation? The second part of this question has been investigated, though results are inconsistent. Porous pavements increased root and shoot extension and biomass of seedlings relative to impervious pavements under

Abbreviations: IP, impervious concrete pavement; IP+, impervious concrete pavement with gravel base; PP, porous concrete pavement; PP+, porous concrete pavement with gravel base.

* Corresponding author. Tel.: +64 3 364 2128.
E-mail addresses: justin.morgenroth@canterbury.ac.nz (J. Morgenroth), bscharenbroch@mortonarb.org (B.C. Scharenbroch).

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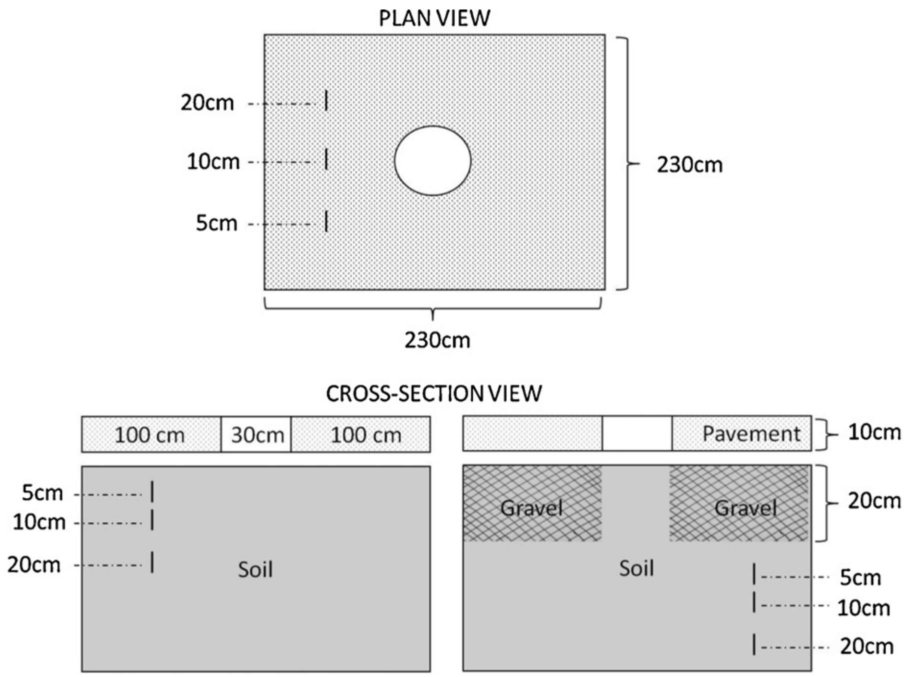

Fig. 1. Plan and cross-sectional view of plot designs for pavement treatments with and without a gravel base. Soil moisture sensors are positioned at 5 cm, 10 cm, or 20 cm beneath the pavement, or the gravel depending on the treatment.

specific conditions (Morgenroth, 2011; Morgenroth and Visser, 2011), but mature trees were unaffected (Volder et al., 2009). It is reasonable to expect that any tree growth differences related to porous pavements are caused by changes in underlying soil conditions. This paper tests the hypotheses that soil water and chemical characteristics are altered by pavements, and also that they differ beneath porous and impervious pavements. In doing so, we explore how pavement porosity and design affect the soil conditions known to influence the growth of urban vegetation.

2. Methods

2.1. Study site

The site for the study was a council-owned tree nursery in Christchurch, New Zealand (latitude: −43.493, longitude: 172.437). Christchurch has a temperate climate, characterized by mean daily maximum temperatures ranging from c. 10 °C in July to 21 °C in January (McGann, 1983). Dry north-westerly winds occur during spring and summer, when temperatures can reach 30 °C and relative humidity can drop to 20–40% (McGann, 1983). Rainfall ranges from 600 to 700 mm annually and is generally evenly distributed throughout the year, with a tendency for slightly higher early winter precipitation (McGann, 1983). The top meter of soil at the experiment site is a fine sandy loam (Raeside, 1974) overlying a deposit of greywacke sand and gravel, a remnant of alluvial outwash (Brown and Weeber, 1992). Greywacke is a sedimentary rock consisting of angular fragments of quartz and feldspar.

2.2. Site preparation and experimental design

In July 2007, prior to installing pavements on site, soil was cultivated to remove existing turf and ensure uniform physical conditions to 30 cm depth. Resulting mean sampled bulk density of this upper layer was 1.26 mg m^{-3} ($n = 5$, $s.e. = 0.07$). Following site preparation, 25 plots were established in a 5 × 5 pattern with interplot distance measuring 50 cm in all directions. Plot size and layout were restricted by available space. Plot treatments were installed in an augmented factorial design consisting of controls (no pavement, exposed soil) and four different pavement treatments split evenly amongst plots, such that five replicates existed per treatment. Treatments were randomly assigned to plots. Herbicide was applied to control plots as necessary to keep the surface free of vegetation. The pavement treatments, measuring 2.3 m × 2.3 m, were based on the factorial combination of pavement type (2 levels: porous, impervious) and pavement profile design (2 levels: with or without gravel base) (Fig. 1). The resulting four treatments were impervious concrete pavement (IP), impervious concrete pavement with gravel base (IP+), porous concrete pavement (PP), and porous concrete pavement with gravel base (PP+). It is important to note that as part of a larger research program (see Morgenroth, 2011; Morgenroth and Visser, 2011), trees were planted in the centre of each plot, with a 30 cm diameter circular cutout made in the pavement to facilitate tree planting (Fig. 1).

The distinction between the two levels of pavement profile design is related to preparation of the profile below the paved surface and was intended to represent differences between a low and high load bearing pavement. In IP and PP plots, profile preparation was limited to levelling the topsoil with a 500 kg roller. In contrast, in IP+ and PP+ plots, topsoil was removed to a depth of 20 cm, exposing the subsurface soil which we termed the subgrade. A 20 cm deep base layer of uniformly graded, 20–40 mm greywacke gravel was installed above the subgrade. Finally, plots were levelled with a 500 kg roller. The difference between the two pavement profile designs is related to the inclusion (or exclusion) of a gravel base and the soil strength of the subgrade resulting from plot preparation. Because plots with a gravel base had their topsoil removed, the soil strength of their subgrade exceeded those without the gravel base. Soil strength was measured via a soil compaction meter (Spectrum Technologies, Inc., Plainfield, IL) in accordance with ASAE Standard EP542 (2002). The compaction meter recorded soil strength at 5 cm depth increments (down to 30 cm) for twelve positions within each plot. Mean values ($n = 60$) differed significantly amongst treatments ($p < 0.001$), and were 892 kPa (*s.e.* = 111), 874 kPa (*s.e.* = 125), 808 kPa (*s.e.* = 112), 2458 kPa (*s.e.* = 163), and 2363 kPa (*s.e.* = 162) for control, IP, PP, IP+ and PP+ respectively.

Both IP and IP+ plots were overlaid by 100 mm impervious concrete comprised of 1260 kg of 13 mm rounded aggregate, 700 kg sand, 250 kg Portland cement, and 160 kg water per cubic meter. Both PP and PP+ plots were overlaid by 100 mm porous concrete comprised of 1523 kg of 6 mm angular aggregate, 243 kg Portland cement, and 50 kg water per cubic meter (Firth Industries, Christchurch). Portland cement is comprised of calcium silicates and sulphates, and oxides of aluminium, iron, sodium, potassium, and magnesium. The porous mix design was specified to achieve 30% porosity, however tested core samples achieved only 11% porosity (ASTM, 2008). Though under specification, the porosity is unlikely to have impeded precipitation infiltration (de Solominihac et al., 2007). Measured hydraulic conductivity of 1.04 cm s^{-1} in the core samples exceeded local standards for porous pavement permeability (ACC, 2003).

2.3. Data collection

2.3.1. Soil moisture

To measure soil moisture beneath pavements, three probes (ECH_2O EC-20, Decagon Devices, Inc.) were buried 5 cm, 10 cm, and 20 cm beneath the soil surface halfway between plot centre and edge (75 probes in total) of the 25 plots. Sensors were inserted parallel to the soil surface, with their flat surface vertical to minimise hydrological disturbances. Soil volumetric moisture content (θ_{soil}) was measured every 5 min (then averaged by the hour) for 42 weeks spanning from June 2008 to March 2009. Following previous authors (e.g. Baumhardt et al., 2000; Lane and Mackenzie, 2001) soil moisture probes were calibrated for use at the study site using the following calibration:

$$\theta_{soil} = 1.2447 \cdot \theta_{probe} + 3.5422$$

Here θ_{soil} (%) is the calibration-adjusted, volumetric soil water content, and θ_{probe} (%) is the ECH_2O probe predicted volumetric soil moisture content from the manufacturer's calibration. By post-processing the data with this calibration, the accuracy of θ_{soil} is reportedly ±2% (Decagon Devices Inc., 2006).

As a point of reference, the permanent wilting point (PWP at 1.5 MPa) and field capacity (FC at 0.01 MPa) of the soil were measured from samples extracted from 5 to 10 cm depth. The PWP of the soil is 11.1% (v/v) and was measured by pressure plate (Model 1500 Ceramic Plate Extractor, Soil Moisture Equipment Corp., Santa Barbara, CA), while the field capacity measured via tension tables is 27.9% (v/v). It is important to note that because of the sampling depth, these values may not be representative of all treatments. In particular both IP+ and PP+ treatments where the upper 20 cm of soil was replaced with a gravel base.

2.3.2. Soil chemistry

In March 2009, pavements and gravel layers were removed, allowing underlying soil to be accessed. Four soil sub-samples per plot were collected from the uppermost 10 cm soil by a 16 mm internal diameter soil probe (AMS, Inc., American Falls, USA) and bulked together such that a single composite sample could be analysed for each plot. Analysis undertaken by Lincoln University laboratories included determination of pH, as well as total available concentrations of calcium (Ca), potassium (K), magnesium (Mg), sodium (Na), iron (Fe), and aluminium (Al) via ICP-OES (Inductively Coupled Plasma-Optical Emission Spectroscopy). Soil samples (0.7 g) were first digested in 5 ml of concentrated nitric acid (HNO_3) (70%, 15.7 M) and 5 ml of hydrogen peroxide (H_2O_2) (30%, 9.8 M), following similar methods to Sah and Miller (1992).

2.4. Statistical analysis

The factorial combination of pavement type and pavement profile design, plus a true control (bare soil) required that mean volumetric soil moisture, pH, and soil nutrient concentrations be compared via one-way analysis of variance (ANOVA) using orthogonal, a priori, single degree-of-freedom contrasts to examine treatment effects, and interactions of interest (Marini, 2003). Contrasts were as follows:

1. Control versus all pavement treatments.
2. Main effect (pavement profile design): ±compacted subgrade and gravel base.
3. Main effect (pavement type): porous or impervious.
4. Interaction effect: pavement profile design × pavement type.

All significant differences are reported for $p < 0.05$, unless otherwise specified. Analyses were performed using the R statistical package, version 2.8.1 (R Development Core Team, 2008).

3. Results

3.1. Effect of pavement on underlying soil moisture

Soil moisture differences resulting from overlying pavements occurred throughout the majority of the study period, but the duration of treatment-related statistically significant differences depended on pavement type, profile design, and measurement depth. Due to the seasonal variability of the soil moisture data, generic inference about the effects of pavement was impossible. So, data were split into 4 time periods: early winter (weeks 1–9), late winter (weeks 10–15), spring–summer (weeks 16–37), and early autumn (weeks 38–42).

3.1.1. Early winter (weeks 1–9)

During early winter, two patterns were apparent. In the uppermost 10 cm of soil, θ_{soil} was lower beneath pavement whose profile included a gravel base than in those plots without the gravel base (Fig. 2). Pavement porosity only became a significant factor deeper in the soil profile. Soil moisture was greater beneath porous rather than impervious pavements for the entire early winter period at 20 cm depth, and for most of the early winter period at 10 cm depth.

3.1.2. Late winter (weeks 10–15)

Following persistent and relatively heavy rainfall during early winter, pavement effects on θ_{soil} were muted during late winter. Soil moisture reached maximum values for all treatments and was consistently above field capacity at all depths (Fig. 2). In such conditions, there was no impact of pavement installation, type, or profile design on θ_{soil}.

3.1.3. Spring and summer (weeks 16–37)

From early spring onwards rainfall declined and so too did soil moisture values (Fig. 2). By the end of summer, θ_{soil} in all plots had declined to their lowest levels, though rates of decline differed amongst treatments and depths. Rapid declines were particularly prevalent at shallow depths (5 cm) in control plots. Soil moisture in paved plots decreased more gradually, causing control plots to have significantly lower θ_{soil} than paved plots for 20 of the 22 weeks comprising the spring–summer period (at 5 cm depth). With increasing depth θ_{soil} in control plots decreased more gradually, resulting in a shorter timeframe where control plots

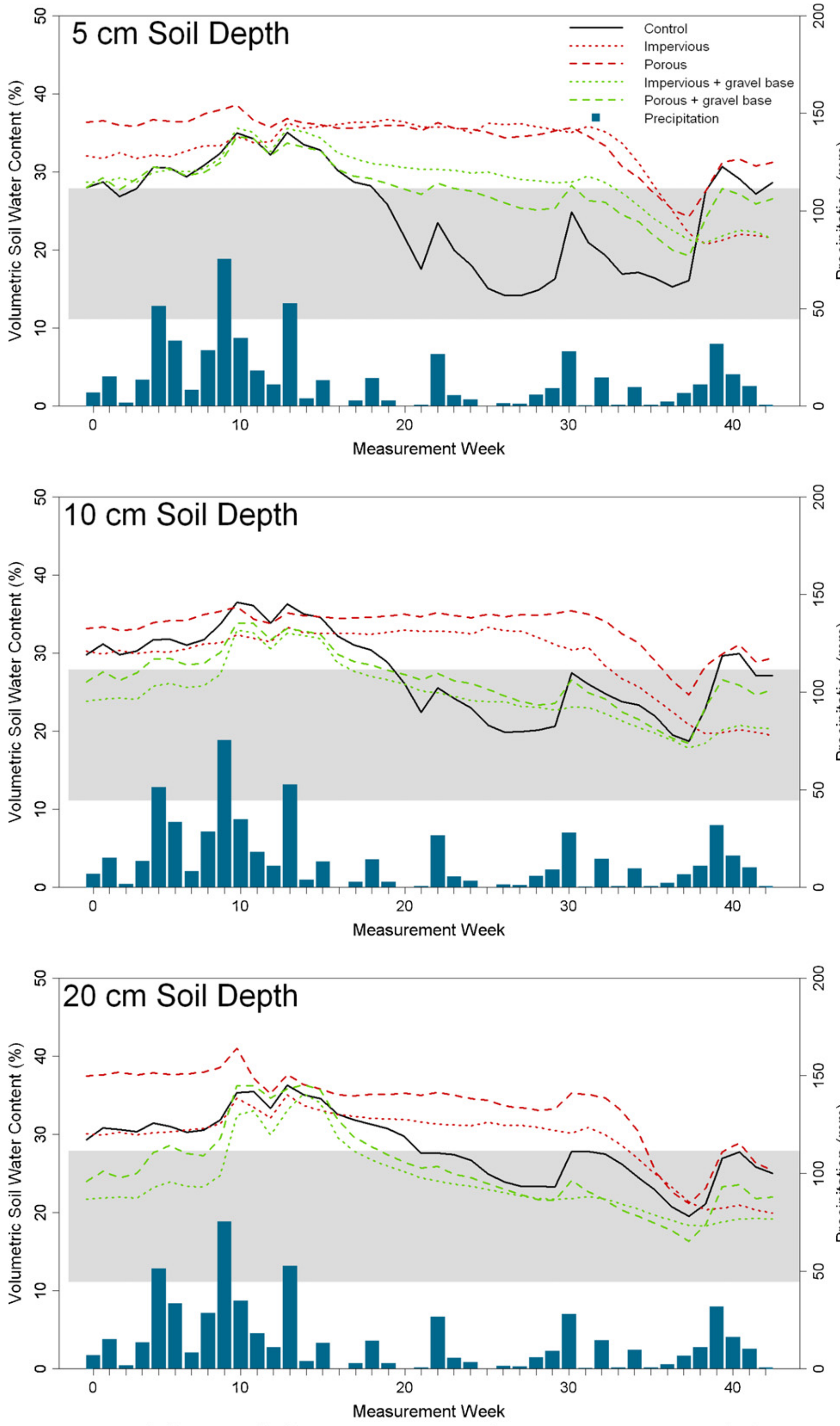

Fig. 2. Mean soil volumetric water content at 5 cm (*top*), 10 cm (*middle*), and 20 cm (*bottom*) depth beneath all treatments. The shaded region represents the plant-available water range between the field capacity and the permanent wilting point. Blue bars represent total weekly precipitation. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

were drier than paved plots. At 10 cm depth, the average θ_{soil} between paved and unpaved plots differed for 10 weeks, while at 20 cm depth, differences only lasted 2 weeks. Differences resulting from pavement profile design were consistent throughout the spring–summer period. The effect was independent of depth and resulted in paved plots without a gravel base having greater underlying θ_{soil} than those with a gravel base (Fig. 2). During this period of relatively low rainfall, the duration of differences attributed to porous versus impervious pavements was very short.

3.1.4. Early autumn (weeks 38–42)

The final time period, early autumn, began with a few weeks of consistent rainfall. In response to this, θ_{soil} in control plots and both porous pavement treatments increased appreciably (Fig. 2). The result is a significant pavement type effect at all depths, whereby plots paved with impervious pavements had lower soil moisture contents than those with porous pavements and control plots.

3.2. Soil moisture response to rainfall events

The magnitude of day-to-day θ_{soil} fluctuations depended on treatment. Unpaved soils exhibited highly variable θ_{soil}, whereas fluctuations beneath pavements were less pronounced. An illustrative example is presented for weeks 37–39 (Fig. 3), where soil moisture in control plots increased sharply in response to precipitation events; mean θ_{soil} increased 11% for control plots during these 3 weeks. Soil moisture beneath porous paving also exhibited an acute response to precipitation events. Increases of 7.8% and 6.5% were measured for porous pavements with and without a gravel base, respectively. On the other hand, θ_{soil} in plots covered by impervious pavements did not appear to be affected directly by precipitation. Soil moisture increased by only 1.1% beneath impervious pavements with a gravel base, and actually decreased by 0.9% for impervious pavements without a gravel base. It appears that impervious pavement cover buffers underlying soil from acute increases of soil moisture resulting from precipitation.

3.3. Soil chemistry

Mean soil pH ranged from moderately acidic in control plots to neutral in some paved plots (Table 1). All pavement treatments significantly alkalinized soil pH relative to control plots, with profile design and type affecting the scale of change. Within pavement treatments, plots with a gravel base had higher mean pH than plots where these were not incorporated in profile design. Meanwhile, porous pavements, regardless of profile design, increased pH relative to impervious pavements (Table 1).

Relative to control plots, pavement treatments did not affect Ca or K concentrations, but did affect concentrations of Na, Mg, Fe, and Al (Table 1). Concentrations of Al, Fe, and Mg were lower beneath paved plots than control plots, whereas Na was greater beneath pavements. Differences in soil nutrient concentrations were also evident amongst the four pavement treatments. Concentrations of Ca, Fe, Mg, and K were lower beneath pavements incorporating a gravel base. Pavement type also affected soil nutrient concentrations. Porous pavements decreased Al and Fe concentrations, but increased K and Na.

4. Discussion

Porous pavements do not guarantee improved tree growth relative to impervious pavements (Volder et al., 2009). However, trees grown in these plots during the same study period (as part of a larger research program) grew up to 50% larger when surrounded by porous pavements (Morgenroth, 2011; Morgenroth and Visser, 2011). The results of this experiment suggest that the contrasting soil moisture and chemical characteristics beneath porous and impervious pavements may be contributing factors to observed tree growth rate differences. A conceptual model is presented in Table 2 and discussed below.

4.1. Soil moisture

For the duration of this experiment, soil moisture was generally greater beneath pavements, supporting similar findings by other researchers (Wagar and Franklin, 1994). It is suggested that two compounding mechanisms are responsible for this result. The first is a distillation process, whereby water vapour diffuses towards, then condenses on, a cool surface. Distillation is caused by diurnal fluctuation in soil temperature, due to soils gaining then releasing heat during a single day. Soils not only gain heat energy and reach their maximum temperature later than maximum air temperature, but also decrease in temperature later than air does (Buchan, 2001; Celestian and Martin, 2004). In the early evening, as air temperature drops and the soil surface cools, water vapour is drawn upwards and condenses on the underside of the pavement, then drains back into the uppermost layer of soil. Though distillation may also occur in unpaved soils, there is no pavement to block moisture migration (and hence retain water in the soil). Also, the diurnal temperature range of paved soils exceeds that of unpaved soils (Asaeda and Ca, 2000). Thus, distillation is amplified beneath paved surfaces.

The second reason for higher soil moisture beneath pavements is that they buffer the soil from atmospheric demand for water, thus minimising evaporation loss. Due to the large interconnected pores that characterize porous pavements, it was initially believed that this pavement type would enable comparable rates of evaporation to control plots. However, in practice the large pores preclude capillary upflow of water through the pavement (Andersen et al., 1999). As water is limited to the soil/pavement boundary and not the pavement/atmosphere boundary, evaporation from beneath porous pavement, like that from beneath impervious pavement, is negligible. Together, distillation and evaporation processes likely drive the differences in soil moisture dynamics beneath paved and unpaved surfaces. In control plots, the combination of weaker distillation and a drying front caused by evaporation results in a depth-dependent soil moisture profile, whereby relatively low soil moisture content occurs at shallow soil depths, and relatively higher soil moisture occurs at deeper soil depths. This explains why the incidence and duration of significant differences between control and paved plots diminished with increasing depth.

The significant difference between pavement profile designs can likely be related to the effect of the gravel base on soil moisture movement. It is believed that the gravel base acted as a capillary break, thereby limiting distillation. The relative effect of distillation between plots with and without a gravel base is illustrated by the soil moisture dynamics during the spring–summer period. Following the winter rains mean θ_{soil} in all plots were statistically similar. By the end of summer, θ_{soil} in plots with gravel bases declined on average 9.4%, while in plots without a gravel base, decreases averaged only 2.2%. We infer that the faster rate of θ_{soil} decline is related to the inclusion of a gravel base and that this limited distillation. Without distillation to replenish water in the surface soil, θ_{soil} was lower in plots designed with a gravel base.

Though soil moisture beneath porous and impervious pavement treatments were generally similar, differences did occur whereby θ_{soil} beneath porous pavements exceeded that beneath impervious pavements. Naturally, porous pavements allowed for more rapid infiltration of precipitation, thereby ensuring greater θ_{soil}. Why then would θ_{soil} beneath porous pavements not have been greater year round, instead of only during particular weeks? The high soil

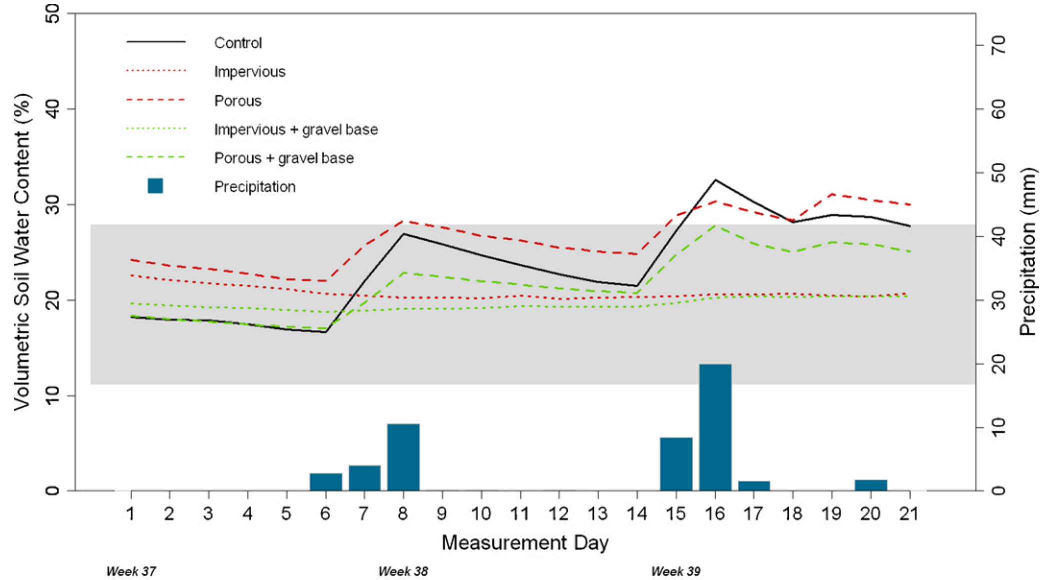

Fig. 3. Daily response of soil moisture (average of 5 cm, 10 cm, and 20 cm values) to precipitation during weeks 37–39. The shaded region represents the plant-available water range between the field capacity and the permanent wilting point.

Table 1
The effect of pavement type and profile design on soil pH and soil nutrient concentrations (uppermost 10 cm). Values shown represent means (1 standard error). The bottom half of the table shows *p*-values for single degree-of-freedom contrasts. $^{*}p < 0.05$.

Treatment	Reaction	Soil nutrient concentration (mg kg^{-1})					
	pH	Aluminium	Calcium	Iron	Magnesium	Potassium	Sodium
Control	5.75 (0.03)	5.90 (0.40)	891 (32)	5.35 (0.37)	81.1 (2.6)	164 (9.3)	28.7 (2.0)
Impervious	6.00 (0.07)	3.91 (0.58)	918 (30)	4.28 (0.26)	80.9 (2.0)	184 (5.8)	35.9 (3.1)
Porous	6.35 (0.05)	1.99 (0.38)	912 (28)	2.44 (0.33)	74.4 (1.7)	225 (8.8)	40.9 (2.7)
Impervious + gravel base	6.26 (0.03)	3.39 (0.35)	812 (43)	2.00 (0.24)	60.2 (2.5)	121 (5.5)	25.7 (1.4)
Porous + gravel base	6.58 (0.06)	1.80 (0.52)	880 (34)	1.35 (0.26)	58.1 (3.1)	147 (5.0)	44.8 (3.3)
Control versus all pavements	<0.0001*	<0.0001*	0.77	<0.0001*	<0.0001*	0.54	0.01*
Main effect (profile design)	0.001*	0.45	0.04*	<0.0001*	<0.0001*	<0.0001*	0.25
Main effect (pavement type)	<0.0001*	<0.0001*	0.36	<0.0001*	0.08	<0.0001*	<0.0001*

moisture contents below both porous and impervious paving for most of the measurement period may have precluded any appreciable effect of infiltration. This is because wet soils can retain relatively less additional water than dry soil, thus partly negating any impact of increased infiltration via porous pavements. The data support this, as significant soil moisture differences, resulting from pavement type, occurred only when pre-rainfall soil moisture was relatively low, or following a period of substantial soil moisture decline. Soil moisture in early autumn is crucial for illustrating this point. Following a summer of low and intermittent precipitation, soil moisture had dropped to their minimums for all treatments. Then, several weeks of consistent rainfall saw an acute increase in θ_{soil} for control plots and both porous treatments. On the other hand, θ_{soil} in plots covered by impervious pavements increased by only a small margin beneath IP+ plots and actually decreased beneath IP plots.

The knowledge that soil beneath pavement was generally wetter than unpaved soil and that porous pavement allowed infiltration of rainfall more so than impervious pavement has implications for urban design. In areas where droughts are expected to increase as a consequence of climate change, porous pavements may be a valuable form of water sensitive urban design (analogous to low-impact design in North America and Sustainable Urban Drainage Systems in the United Kingdom). Compared with

Table 2
A conceptual model showing the relative impacts of porous and impervious pavements and their design on soil moisture and chemistry.

Process	Treatment				
	Control	Impervious	Porous	Impervious + gravel base	Porous + gravel base
	Soil	Impervious Pavement Soil	Porous Pavement Soil	Impervious Pavement Gravel Base Soil	Porous Pavement Gravel Base Soil
Infiltration	High	Low	High	Low	High
Distillation	Low	High	High	Low	Low
Alkalinization	Low	Moderate	High	Moderate	High
Mineral weathering	Moderate	Moderate	High	Low	Moderate

impervious pavement, there is potential for porous pavement to mitigate drought stress for urban vegetation.

The results of this study must be considered in context. Due to space restrictions at the study site, plot size and inter-plot distance was limited. One concern was that pavements measuring 230 cm × 230 cm may not be sufficiently large to influence soil moisture dynamics. However, significant differences amongst the treatments showed that soil moisture was affected by treatments, thus dispelling that concern. Another concern was that within plot soil moisture values may not only be entirely reflective of treatment, but also the treatment of adjacent plots due to rainfall runoff. In sandy loams, like those at the study site, lateral water flow is limited due to high hydraulic conductivity (Siyal and Skaggs, 2009). Moreover, the randomized plot design will have minimised the statistical consequence. Given the area limitations of the study site, we believe that the chosen experimental design minimises the impact of edge effects on responses to treatments.

4.2. Soil chemistry

Relative to control plots, all pavement treatments increased the mean pH, with further differences related to pavement type and profile design main effects. This result is supported by other studies which have found similar increases in soil pH near or beneath roads (Messenger, 1986; Park et al., 2010). But our results went further than simply showing that pavements can alkalinize underlying soil. Like previous, recent research (Kuang and Sansalone, 2011), we showed that soil was more alkaline beneath porous, rather than impervious pavement. The reasons for this are that porous pavements contain a greater proportion of cement than impervious pavements (Ferguson, 2005) and their hydraulic conductivity is relatively high (Sansalone et al., 2008). So, as rainfall infiltrates through the tortuous pores of the porous pavement, more $Ca(OH)_2$ (in the cement paste) is exposed to water, resulting in greater Ca^{2+} inputs to the underlying soil. This is in contrast to impervious pavements where water is intentionally channelled off the pavement to prevent its infiltration into the soil.

Our results also showed higher soil pH in plots with a gravel base than in those without. The gravel base was comprised of unwashed greywacke stone coated by clay microfine particles (<75 μm) (Muñoz et al., 2010). It is believed that the alkalinization in these plots is attributable to weathering and cation release of the greywacke material (Guimarães, 2010).

The importance of pavement's effect on soil pH is that pH affects mineral solubility in both organic (Lucas and Davis, 1961) and mineral soils (Truog, 1948). Though mineral solubility varies drastically with changing pH, phosphorus, iron, manganese and other micronutrients may be unavailable to plants in alkaline soils (Larcher, 2003), while in acidic soils, aluminium and iron may be present at toxic levels (Sparks, 2003). All nutrients have solubility thresholds and, of those required for plant function, many are known to decrease with increasing alkalinity, including boron, copper, iron, zinc, magnesium, potassium, and phosphorus (Larcher, 2003; Lucas and Davis, 1961). So, if pavement (in particular porous pavement) increases the pH of soils to values which limit nutrient solubility, there is potential to affect plant function and growth.

Observed increases in nonacid cations in this research arise from accumulations exceeding removals via leaching from the 0 to 10 cm soil layer. The greatest significant differences for K, Mg, Ca, and Fe occurred between the paved treatments. On average, paved treatments with a gravel base had 53%, 31%, 8%, and 84% lower concentrations of K, Mg, Ca, and Fe compared to pavement treatments without. The gravel base appeared to cause a capillary break, limit infiltration and distillation processes, and overall reduce soil moisture contents of the 0–10 cm layer. The reductions in these cations are likely a result of less water movement and mineral weathering and also reduced distillation and illuviation in the 0–10 cm layer.

Regardless of design treatment, both Na and K in the 0–10 cm soil layer were greater under porous pavement compared to impervious pavement. The possible reasons for this are: (1) porous pavements contain greater proportions of these elements and have greater hydraulic conductivity, resulting in greater inputs of these bases to the underlying soil, and (2) increased soil water under porous pavements led to increased weathering and release of mineral K and Na. It is puzzling that Mg and Ca also did not increase in soil under porous compared to impervious pavement. Of the metals studied, Mg is the most mobile (Schaetzl and Anderson, 2005). Could it be that increased Mg inputs associated with porous pavements were quickly dissipated through relatively faster leaching out of the 0–10 cm layer? Could the naturally higher background levels of native Ca in the soil be masking possible treatment induced differences associated with inputs from porous pavement?

5. Conclusion

These results expand on previous research by the authors (Morgenroth and Buchan, 2009) by extending the temporal component of soil moisture measurement to nearly a complete year, thereby taking into account important seasonal climatic cycles. During this experiment, soil moisture was consistently higher beneath pavements, except following the winter rains where high soil moisture muted all treatment effects. Pavements also buffered soils from large daily soil moisture fluctuations. The inclusion of a gravel base in the pavement design acted as a capillary break, limiting the distillation effect that brought water to the surface under pavements. Throughout most of the study period, this resulted in lower soil moisture content beneath pavement profiles designed with the gravel base. Though soil moisture differences beneath porous and impervious pavements did not exist for the majority of the measurement period, an important effect was seen during early autumn precipitation events. Impervious pavements prevented the rapid infiltration of water following small rainfall events, whereas porous pavements allowed infiltration. Soil moisture was recharged beneath these porous pavements, but remained at low levels beneath impervious pavements. This is potentially the most important finding of this research, but further work is required to determine whether such late season soil moisture recharges can minimise drought stress for urban vegetation.

Following 19 months covered by pavements, soil pH was altered from moderately acidic to neutral. Effects on pH were greater beneath porous rather than impervious pavement, and also when a gravel base was included in the pavement profile design. This affected mineral solubility, reducing the soil concentration of Al, Fe, and Mg, while increasing the Na concentration beneath pavements. This result is specific to this experiment, but could potentially occur in other acidic soils. Where native soil is neutral or alkaline, the effect of pavements on soil pH (and hence mineral solubility) may differ.

In conclusion, the installation of pavements can alter soil physical and chemical characteristics necessary for plant growth and survival. Porous pavements can increase water availability and alter soil pH and micronutrient availability. Future research could extend or complement this work by generalizing results across a variety of soil types.

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