The Effect of Porous Concrete Paving on Underlying Soil Conditions and Growth of *Platanus orientalis*

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To My Family – Oh the places I've gone!

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Abstract

Urbanisation is characterised by mass migration of people to urban areas and conversion of land from rural to urban land uses. Changes in population dynamics have led to half the world's population living in urban areas; in developed countries, urban dwellers account for three-quarters of the total population. Though populations have shifted from rural to urban areas, people continue to rely on their environment, and trees in particular, for tangible and intangible benefits alike. A great deal of factual and anecdotal knowledge supports the role of trees for ecological, social, and economic well-being. In spite of this, during urbanisation, previously vegetated land is converted to housing, roads, or utility corridors, all of which are necessary to support growing populations.

This thesis investigates tree growth in these modified urban landscapes, in particular, the effects of pavements on urban trees. Pavements are truly pervasive, covering more than half of all land in highly developed urban areas. Their durability and strength are of great importance to transportation, but large-scale soil sealing is not without consequence. Pavements affect the hydrologic cycle, soil and air temperature, and nutrient cycling. Because of their effect on the surrounding environment, pavements inherently affect remnant or planted trees. They are believed to negatively affect tree growth and survival, thereby compromising the ecological, social, and economic benefits otherwise derived from the urban forest.

In recent times, porous pavements have been increasingly installed in favour of impervious pavements. Porous pavements are perceived to be an environmentally-sound alternative to standard impervious pavements. This thesis begins by reviewing the literature concerning porous pavement's effect on underlying soil and urban vegetation, thus illustrating the scarcity of empirical data describing the effect of porous pavement on tree growth. A greater understanding of porous pavement's impact on the surrounding environment is needed, if its installation is to continue.

With this aim in mind, this thesis describes an experiment in Christchurch, New Zealand, which monitored the impacts of porous and impervious pavement on underlying soil conditions, and subsequent tree growth. The experiment comprised 50

Platanus orientalis trees planted in an augmented factorial design, which consisted of controls and four treatments. Trees were split evenly amongst plots, such that ten replicates existed per treatment. The pavement treatments measured 2.3m by 2.3m, and were based on the combination of pavement type (2 levels: porous, impervious) and pavement profile design (2 levels: +/- subbase compaction and gravel base). The resulting four treatments were impervious concrete pavement (IP), impervious concrete pavement with compacted subbase and gravel base (IP+), porous concrete pavement (PP), and porous concrete pavement with compacted subbase and gravel base (PP+). From December 2007 to March 2009, data were collected to determine the effect of these treatments on soil moisture, aeration, pH, and nutrient concentration. Final tree height, stem diameter, shoot and root biomass, and root distribution were also measured at the conclusion of the experiment.

Results of this experiment indicated that the effects of pavement porosity on soil moisture and aeration were dynamic, varying with season and soil depth. Increased soil moisture beneath porous pavements resulted from rapid infiltration following precipitation. This decreased the duration of plant stress resulting from drought. Relative to bare soil, paved plots had consistently greater soil moisture, likely because pavements reduced evaporation. The inclusion of a gravel base in the profile design limited capillary upflow, which resulted in lower soil moisture under pavements designed with a gravel base. Soil aeration was significantly lower beneath pavements relative to unpaved plots. This is likely related to greater soil moisture beneath pavements. Finally, soil pH increased beneath pavements, in particular beneath porous pavements.

Though all growth parameters increased for trees surrounded by porous, rather than impervious pavement, this occurred only in the absence of a compacted subgrade and gravel base. Evidently, the impact of the compacted subgrade superseded the impact of pavement porosity. Furthermore, root growth was relatively shallow beneath pavements, likely due to favourable soil moisture directly beneath pavements.

This research highlights (i) the dramatic effect of pavements on underlying soil conditions; (ii) that pavements do not inherently limit tree growth; (iii) that porous pavements can conditionally improve tree growth; and (iv) that soil compaction limits potential benefits resulting from porous pavements.

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Chapter I

Introduction

1.1 Urbanisation

Urbanisation, the conversion of land from its natural state to an urban one, has occurred more rapidly in recent times due to increasing global population (Chen and Heligman 1994), as well as, technological advances in transportation and agriculture (White and Whitney 1992). This combination caused a great human migration from rural to urban areas. In fact, at the beginning of the new millennium, approximately half the world's population lived in cities (UNCHS 2001). The housing, transportation, and utilities necessary to manage this migration have necessarily contributed to increasing soil degradation (Gray 1972) and decreasing urban greenspace (Detwyler 1972). However, environmental consciousness has developed into a green revolution in which environment is a central theme of new urbanisation. This is called green urbanism (Beatley 2000).

Maintenance and enhancement of the urban forest is vital to green urbanism as woodlots, parks, and individual trees provide ecological, social, and economic benefits. Urban forests improve air and water quality (Heckel 2004; Xiao et al. 1998), moderate extreme temperatures (Long-Sheng et al. 1993), reduce energy consumption (McPherson 1994), increase real estate values (Anton 2005), provide wildlife habitat (Dunster 1998), and provide intangible benefits including aesthetic and recreational amenities. In spite of the benefits provided by trees, difficulties remain in maintaining and enhancing the urban forest (Kielbaso 1990). One alleged challenge to the urban forest, and a symptom of urbanisation, is conversion from natural to impermeable surfaces. Buildings comprise roughly 30-35% of impermeable surfaces, while pavements occupy the remaining 65-70% (Ferguson 2005). Pavements are most pervasive in highly developed urban areas, covering more than half of all land (Ferguson 2005). On an absolute scale, there are an estimated 2.82km of paved roads per thousand people, or roughly 17 million kilometres of paved roads globally (Canning 1998). Though they swathe a vast area, can impervious pavements hinder green urbanism by impeding urban forest development?

1.2 Pavements and Urban Trees

It is widely believed that impervious pavements negatively influence the vitality of urban trees through their effects on the environment in which they grow (Iakovoglou et al. 2001; Kjelgren and Clark 1994; Pitt et al. 1979; Quigley 2004; Schröder 2008). It is important to recognise that pavements are not simply a surface course of concrete or asphalt covering the soil. Often, pavements are characterised by a profile designed to bear loads. These engineered pavements can include a number of structural layers, but at the very least, they include a compacted subgrade and gravel base on which the concrete or asphalt surface course is installed. In recent years, it has been recognised that the soil compaction resulting from this pavement profile design may contribute to tree decline.

Though studies fail to separate the effects of the surface course from the profile design, it is often concluded that pavements negatively impact urban tree growth. One dendrochronological study found an acute reduction in basal growth coinciding with the installation of pavements; these were believed to have caused a decrease in available oxygen and moisture (Petersen and Eckstein 1988), both of which are necessary for optimal physiology. Pavement's alleged role in reducing the diffusion of oxygen into the soil is supported by others (Craul 1985; Jim 1997; Macdonald et al. 1993), but its impact on soil moisture is more contentious. Pavements may reduce soil moisture by precluding infiltration (Craul 1985; Cutler 1993; Jim 1997; Sanders 1986; Yau 1982), but they may limit evaporation, thereby increasing soil moisture (Wagar and Franklin 1994; Whitlow et al. 1992).

Though its effect on soil moisture is disputed, pavement's effect on soil and air temperature is clear. On a landscape scale, relative air temperature is highly correlated to impervious surface cover (Henry and Dicks 1987; Tratalos et al. 2007). This is mirrored at a smaller scale where air temperatures above sealed surfaces are significantly higher than surrounding vegetated areas (Kjelgren and Montague 1998). The impact of increased air temperature on urban trees is related to the vapour pressure deficit; higher air temperature and lower relative humidity above pavement results in a high vapour pressure deficit, which has an implicit negative effect on leaf gas exchange and hence, tree development (Montague and Kjelgren 2004; Mueller and Day 2005). In addition to hotter air temperature, the rhizosphere temperature is significantly higher beneath sealed surfaces (Celestian and Martin 2004; Graves 1994; Graves and Dana 1987), and can often exceed thresholds known to cause injury to root tissues (Ingram et al. 1989).

Concrete pavements in particular are also believed to affect soil chemistry. The dissolution of limestone from the concrete pavement raises the pH and renders soils more alkaline, therefore affecting nutrient availability (Messenger 1986; Ware 1990). Taken together, pavements affect both soil chemistry and physics. Given that a great majority of urban tree problems are thought to begin in the soil (Patterson et al. 1980), it is comprehensible that pavements may have both direct and indirect effects on tree growth and survival.

1.3 Porous Pavements

Until the 1960s, pavements and permeability were mutually exclusive; installing pavement led to a loss of surface permeability. However, the advent of porous paving changed this and now it is possible to pave urban surfaces and maintain permeability to air and water. In contrast to the perception that pavement hinders tree growth, porous paving is believed to promote tree growth and survival. Porous paving is allegedly “ideal for protecting trees in a paved environment” (Tennis et al. 2004) and can “increase the longevity of trees by improving moisture and oxygen relations” (Ferguson 2005).

These theories remain untested and, in fact, the only study to directly relate surface permeability and tree growth failed to find a significant correlation (Vrecenak et al. 1989). Nevertheless, the logic is reasonable, as porous pavements do not present a barrier to water and air infiltration, and have also been linked with decreased soil and air temperatures (Asaeda and Ca 2000). So, if porous paving can improve the environment in which trees are planted by facilitating rainfall infiltration and oxygen diffusion into the soil, as well as, reducing limiting soil and air temperature, then tree growth and survival may improve.

1.4 Organisation of Thesis

The fact remains that little is known about the effects of porous pavements on their environment, and even less is known about their effects on trees. This thesis endeavours to begin addressing this knowledge gap. It does so by first presenting the current state of knowledge regarding porous paving. The four chapters that follow present the results of a trial initiated to monitor the effects of pavement treatments on underlying soil conditions and tree growth. The first two chapters explore the effects of 2.3m by 2.3m concrete pavement pads on underlying soil moisture, aeration, pH, and nutrient concentration. The two subsequent chapters detail the above- and below-ground growth response of 50 *Platanus orientalis* trees, grown in the pavement environments. Finally, a summary of these results is presented along with practical implications of the results and directions for future research.

Chapter II

Literature Review

2.1 Porous Pavement

Porous paving is known by a number of different, but similar names including pervious paving, permeable paving, percolating paving, gap-graded paving, open-graded paving, enhanced-porosity paving, and no-fines paving. Many of these names allude to the porosity of the pavement, which is permeable to air and water. In addition to the different names, pavements can be classified by type. Ferguson (2005) identifies nine families of porous paving: porous aggregate, porous turf; plastic geocells, open-jointed paving blocks, open-celled paving grids, porous concrete, porous asphalt, soft porous surfacing, and decks. An often overlooked distinction exists between porous and permeable paving. Porous paving is capable of infiltrating water across the entire surface, whereas permeable paving is a patterned surface comprised of impermeable material separated by large voids (Pratt et al. 2002). Examples of the former are porous concrete or asphalt, while the latter includes open-jointed paving blocks and open-celled paving grids. This literature review focuses on porous paving, in particular porous concrete and asphalt.

2.1.1 History

The use of porous cementitious material for buildings is hundreds of years old. The use of porous materials in pavements, however, was first used in an experimental road in England in the 1960s (Maynard 1970). The following decade, applications of porous paving expanded to mainland Europe with the intention of providing safer transportation via a skid-resistant surface course. Roads were built in Belgium (Van Heystraeten and Moraux 1990), Switzerland (Isenring et al. 1990), Spain (Ruiz et al. 1990), and the Netherlands (Van der Zwan et al. 1990). In the United States of America, porous paving was first used in Florida during the 1970s. It was touted for its environmental benefits and consequently, by the mid-1990s a number of other American states were exploring its benefits (Ferguson 2005). The catalysts for installing porous pavements in the United States have been the Clean Water Act

(USEPA 1972) and the National Pollutant Discharge Elimination System (USEPA 2001). These regulations pertain to stormwater management and require decreasing the amount of surface runoff, as well as treating water at the source. Since both of these requirements are met by porous pavements, there has been greatly increased installation of porous surfacing for compliance purposes. Interestingly, porous paving was adopted on two continents for different reasons, in Europe for road safety and in North America for environmental benefits. This highlights its functionality.

2.1.2 Physical Characteristics

Porous pavement is coarse and stony in appearance and is characterised by relatively large interconnected voids (Jain 1966). Standard asphalt or concrete pavement mix designs include water, a binder, and aggregate graded from sand to coarse gravel. In a porous pavement, sand is excluded from the mix, hence the alternative name, no-fines pavement. The exclusion of fine aggregate from the mix allows voids to form between stones.

The descriptive characteristics of porous pavements are its void ratio, permeability, and compressive strength. To a certain extent, a trade-off exists between permeability and strength properties. Permeability is positively correlated with void ratio and these are both negatively correlated with strength parameters (Schaefer et al. 2006). Void ratio typically ranges from 10-35% and though hydraulic conductivity decreases significantly below 15% porosity (Meininger 1988), lower porosity pavements can still meet permeability requirements (de Solominihac et al. 2007; Youngmin and Grasley 2008). Though hydraulic conductivity can reach 2000cm/hour in experimental settings (Schaefer et al. 2006), a pavement's permeability will decrease over time and depends on clogging and maintenance. The strength of porous pavement is not equivalent to that of standard structural pavements so, for this reason, engineers abide by rules of thumb, such as '50% thicker than regular concrete pavement' (Offenberg 2007). Despite its relatively lower strength, by using an appropriate binder and adequate base material, porous pavements can be made to meet specifications (Nicholls 1999).

2.1.3 Shortcomings and Benefits

The physical characteristics of porous paving contribute to its functionality, but also to some potential shortcomings. Due to its large pores, an often cited drawback is its propensity for clogging (ACI 2006; Argue 2004; Scholz and Grabowiecki 2007). Dirt and other particulate matter may clog the pores, rendering a porous pavement, impermeable. But, a properly designed and maintained porous pavement will not be prone to significant clogging (Ferguson 2005). In fact, some research has shown that even with deliberate application of particulates, pervious pavement retains high levels of permeability and regular maintenance can restore permeability to nearly 100% of its original value (Sorvig 1993). Regardless of whether clogging occurs, intentionally clogged porous pavement retains sufficient permeability to infiltrate typical rainfall events, so clogging is an inconsequential concern (Haselbach et al. 2006).

Another contentious aspect of porous paving is its cost. Some studies suggest the cost of installing porous paving exceeds regular paving installation (Booth and Leavitt 1999). However, the functionality of porous paving suggests that it should be considered as a part of a stormwater management system. In this capacity, it is more cost effective than the sewers, drains, and pipes necessary for stormwater management in traditional pavements (Adams 2003; Sorvig 1993; Tennis et al. 2004). So while the material costs of porous paving do exceed the cost of impervious paving, this difference is recovered when considering all aspects of a pavement installation including stormwater management necessary to meet specifications.

The benefits of porous paving far exceed the drawbacks. In Europe, porous paving is installed as a friction course on roads, where it reduces traffic noise and improves safety (Dreelin et al. 2006). The pores decrease the strength of air pumping by absorbing energy and thus reduce the noise created by car tires in contact with the pavement (Bendtsen and Andersen 2005; Swanlund 2005). The pores play another vital role by infiltrating water, thus eliminating water pooling (Abbot and Comino-Mateos 2003). This eliminates splashing and reduces reflections on the pavement surface, thereby improving visibility (Van Heystraeten and Moraux 1990). Also, without pooling, tires can maintain contact with the pavement thus avoiding aquaplaning (Nicholls 1999; Van Heystraeten and Moraux 1990). These acoustic and hydraulic properties have led to increased installation of porous paving throughout Europe (Pagotto et al. 2000).

In North America, porous paving is installed primarily to manage stormwater. Traditional stormwater management required the collection of stormwater by curbs, gutters and drains, and then eventual disposal in a retention basin after being transported great distances in subterranean pipes (Field et al. 1982). The inevitable runoff from these systems leads to flooding, high peak stream flow, stream bank erosion, sediment transport, and increased pollutant loads (Nelson and Booth 2002; Trimble 1997; Whipple et al. 1981; Winter and Duthie 1998). Contemporary stormwater management has evolved to take advantage of soils' intrinsic role as a water reservoir. Porous pavements, with their large interconnected voids, permit rainfall infiltration as opposed to runoff (Abbot and Comino-Mateos 2003; Bean et al. 2007). The porous paving and bedding material behave as filters, removing pollutants from the stormwater, including suspended solids, heavy metals, and hydrocarbons (Legret and Colandini 1999; Pagotto et al. 2000). The filtered rainwater then restores groundwater levels (Boving et al. 2008). This functionality has led to porous pavements being incorporated into water sensitive urban design (CCAA 2004). In fact, the EPA lists pervious pavements amongst its best management practices for the management of stormwater runoff (Tennis et al. 2004).

Clearly, ample evidence supports the role of porous paving in stormwater management (Tennis et al. 2004) and transportation safety (Dreelin et al. 2006), however, beyond this scope only basic details of its environmental impact are known. Some research describing the effects of porous paving on its environment exists, in particular the effect of porous paving on underlying soil moisture and temperature. Rainfall infiltration through porous paving has been observed in numerous studies (e.g. Bean et al. 2007). Coupled with negligible evaporation (Asaeda and Ca 2000), this may lead to higher soil moisture beneath porous paving than beneath impervious paving. Also, porous paving elevates the temperature of underlying soil to levels comparable, though marginally lower than impervious pavement; the same is true of the air temperature (Asaeda and Ca 2000).

Given its potential for modifying the hydrological (Bean et al. 2007) and thermal (Asaeda and Ca 2000) microclimate, the increased installation of porous paving may affect surrounding vegetation, in particular, street trees which comprise a valuable portion of the urban forest. To date, there has been little evidence linking porous paving and possible effects on urban trees. This, however, has not prevented authors from speculating that porous pavements provide vast benefits to urban trees, improving soil moisture and aeration status (Brown 2003; Edwards and Gale 2004; Ferguson 2005; Tennis et al. 2004).

2.2 Urban Surface Cover Types

Despite the absence of a direct link between tree development and porous paving, there is a comprehensive body of literature describing tree growth in other permeable and impermeable surface types including standard pavement, turf, and mulch. By identifying factors which affect the growth and survival of trees surrounded by various urban surface types, the following review will help illustrate the potential effects of porous pavements on urban trees.

2.2.1 Pavement

Pavement has often been associated with compromised tree growth (Iakovoglou et al. 2001; Kjelgren and Clark 1994; Petersen and Eckstein 1988; Quigley 2004), though the mechanisms responsible for this decrease are not as easily identified. Some possibilities include water stress, inadequate soil aeration, nutrient deficiency, soil compaction, increased temperature, vandalism, or an interaction of these factors.

It had often been suggested that pavements precluded infiltration, thereby reducing soil moisture, causing moisture deficiency in street trees (Foster and Blaine 1978; Gerhold et al. 1975; Roberts 1977). Anecdotal evidence has shown that this is not always the case. Hundreds of disinterred street trees in New York City showed symptoms of root rot due to water saturation (Berrang et al. 1985). Empirical research also contradicts this popular belief, as a number of studies have established that soil moisture is greater beneath pavements than in surrounding soils (Wagar and Franklin 1994). Whitlow and Bassuk demonstrated that soil moisture supply was not limiting to trees surrounded by pavements. Though temporary water deficits did occur due to high atmospheric demand, nocturnal recovery to the previous day's predawn water potential always occurred, thus signifying the absence of chronic moisture stress (1987).

While it is unlikely that soil moisture is limiting beneath pavements, the effect of pavement on above- and below-ground temperature may be detrimental to tree development. Incoming solar radiation can heat pavement surfaces to much higher temperatures than their vegetated surroundings (Montague and Kjelgren 2004). One reason for this is an absence of evaporational cooling (Doll et al. 1985). Radiation energy can be conducted into the underlying soil, thereby increasing soil temperatures to extreme levels (Celestian and Martin 2004; Graves and Dana 1987; Halverson and Heisler 1981). Soil temperatures exceeding 30°C, often found beneath pavement, can negatively affect root physiology (Graves 1994; Ruark et al. 1983).

Another impact of elevated pavement temperature is its role in the atmospheric demand for water. Greater surface temperature can result in increased air temperature and decreased relative humidity (Whitlow and Bassuk 1988). Consequently, trees growing in pavement can be subjected to high leaf vapour pressure deficits, increased transpiration, and greater water loss (Kjelgren and Clark 1994; Potts and Herrington 1982). Conversely, depending on the species and climate, a plant's response to high vapour pressure deficit is to close their stomata, reducing transpiration and water loss (Kjelgren and Clark 1993; Montague et al. 2000; Turner et al. 1984). While stomatal closure limits water loss, it also limits gas exchange, and hence reduces photosynthesis and growth.

Whilst soil moisture supply beneath pavements appears non-limiting, the atmospheric demand for water in trees surrounded by pavement can lead to temporary water deficits (Whitlow et al. 1992). High atmospheric demand results, in part, from high surface temperatures associated with pavements. High temperatures are also found beneath pavements at levels high enough to limit tree development (Graves 1994). So, if pavement hinders tree development, it is unlikely that this results from soil moisture deficiency. However, the heat storage capacity of pavements, and hence their ability to modify root-zone temperature and atmospheric demand for water, may lead to compromised tree growth.

Arguably the most severe limitation to tree growth associated with pavements is related to underlying soil compaction. Many pavement design profiles include structural layers such as a compacted subgrade and gravel base below the surface course. The result is that tree roots must grow in a compacted soil medium, which can negatively impact root elongation (Sinnett et al. 2008) and shifts root respiration from aerobic to anaerobic (Kozlowski 1999). The cumulative effect of soil compaction was summarised by Smiley et al. (2006) who showed marked growth and health benefits for trees planted in non-compacted treatments, including suspended pavements and engineered soils.

Means to achieve lower soil compaction beneath pavements have been trialled, and include the use of specially designed pavement profiles, whereby the pavements are engineered to withstand heavy loads, while avoiding soil compaction (e.g. vaulted pavements, CU-Soil^{TM}). The short-term successes of these alternatives have been proven (Buhler et al. 2007; Smiley et al. 2006), however, their prevalence is not widespread.

2.2.2 Turf

The use of turf or grass around urban trees has both benefits and drawbacks, relative to other surface cover types. While some studies have demonstrated that turf hinders tree development relative to mulch or bare soil (Fraedrich and Ham 1982; Green and Watson 1989; Watson 1988), others have shown that trees benefit from a vegetated surrounding (Montague et al. 2000; Mueller and Day 2005). The deleterious mechanisms involved are primarily competition for soil moisture (Coll et al. 2004; Watson 1988) and nitrogen (Coll et al. 2004; Tworkoski and Glenn 2001), while the beneficial mechanisms include cooler air temperature and decreased vapour pressure deficit (Montague and Kjelgren 2004).

Through a combination of transpiration and evaporation, turf surface covers are often associated with reduced soil moisture (Clary et al. 2004; Coll et al. 2004). In addition to competing with trees for water, grasses compete for nutrients, in particular, nitrogen (Coll et al. 2004; Tworkoski and Glenn 2001). Turf's competitive advantage for nitrogen uptake is due in part to their dense root systems comprising mainly thin roots with high absorptive capability (Robinson et al. 1991). This competitive interaction can result in plant moisture stress (Close et al. 1996) and nitrogen deficiency (Tworkoski and Glenn 2001), both of which reduce development.

In spite of these competitive advantages, turf can positively affect tree development by creating conditions conducive to gas exchange (Montague and Kjelgren 2004). Evapotranspiration has the dual effect of cooling air temperature and increasing relative humidity, the effect of which is a reduction in vapour pressure deficit between leaves and the surrounding air (Montague et al. 2000; Mueller and Day 2005). Consequently, stomata remain open and gas exchange can continue unimpeded, thereby facilitating photosynthesis (Montague et al. 2000; Mueller and Day 2005). This benefit is limited by soil moisture; low soil moisture will induce stomatal closure irrespective of atmospheric vapour pressure deficits.

Turf's benefits for trees in urban areas relates to its ability to increase relative humidity while reducing air temperature and leaf vapour pressure deficit. This creates a favourable atmosphere for gas exchange and increased photosynthesis. But, turf can out-compete trees for precipitation and induce moisture stress. Furthermore, competition for nitrogen availability can be deleterious to tree development.

2.2.3 Mulch

Mulch is a permeable surface type, often placed over bare soil or existing vegetation with the intent of suppressing competition and preventing soil moisture evaporation. There exist a variety of different mulches but the two major classes are organic (bark or wood chip) and mineral (crushed brick, lava rock, pea stone) mulches. Many studies have reported improved above-ground growth (Green and Watson 1989; Greenly and Rakow 1995; Samyn and De Vos 2002) and root growth (Watson 1988) through the application of mulch. Thus, in general it is expected that mulch improves the environment in which trees grow.

With respect to soil moisture, mulch can increase moisture infiltration by reducing runoff and preventing soil sealing (Harris 1992; Smith and Rakow 1992). On the other hand, mulch can absorb moisture and so light rainfall or irrigation may not infiltrate through to the roots (Gilman and Grabosky 2004). The pores in mulch reduce capillarity and consequently minimise evaporation (Iies and Dosmann 1999).

A combination of generally increased infiltration and reduced evaporation results in higher soil moisture beneath mulch (Greenly and Rakow 1995; Iies and Dosmann 1999; Watson 1988). This is especially true when mulched sites are contrasted against vegetated sites as transpiration leads to even lower soil moisture (Watson 1988).

Both classes of mulch reduce soil temperature relative to bare soil (Greenly and Rakow 1995; Iies and Dosmann 1999; Montague and Kjelgren 2004), but temperatures tend to be lower beneath organic mulches than mineral mulches (Iies and Dosmann 1999). This effect can be drastic with bare soil temperature doubling that of mulched soil in some cases (Einert et al. 1975). Lower temperature may only be prevalent at the beginning of the growing season as soils beneath mulch are slower to warm (Greenly and Rakow 1995). Given that root function is hindered at temperatures outside the optimal range of 10°C - 30°C (Graves 1994; Ruark et al. 1983), the buffering property of mulch may preclude impeded function during periods of extreme weather. Conversely, given the potential for delayed soil warming, organic mulches, and to a lesser extent, mineral mulches, may delay the onset of root growth at the beginning of a growing season.

A potential drawback of mulch application is its effect on air temperature. Due to a lack of evaporative cooling and re-radiation of solar energy as long-wave radiation, air temperature above mulch is typically higher than above a vegetated surface (Montague et al. 1998). This can increase the vapour pressure deficit between a leaf and the atmosphere, inducing stomatal closure and corresponding decreases in photosynthesis (Montague and Kjelgren 2004).

The specific effect of mulch on soil aeration is divisive. Deep layers of mulch can result in poorly aerated soil (Billeaud and Zajicek 1989; Gouin 1983); however, this is not always the case (e.g. Greenly and Rakow 1995; Watson 1988; Watson and Kupkowski 1991). Anaerobic conditions may present themselves if fine- rather than coarse-textured mulch is applied, but this is not well understood (Hanslin et al. 2005). Nevertheless, as the oxygen necessary for root respiration must enter through the soil surface it is plausible that any material covering the surface could interfere with oxygen diffusion (Watson and Kupkowski 1991).

Depending on the type of mulch used, soil chemistry may be affected. Soil pH beneath organic mulch has been shown to decrease (Hild and Morgan 1993), possibly a consequence of organic acids from decomposing woody material being leached into the soil (Himelick and Watson 1990). However, other studies have shown that soil acidification does not occur beneath pine bark mulches (Greenly and Rakow 1995; Pickering and Shepherd 2000). Under mineral mulch, such as pea gravel, soil alkalinisation may be expected due to the leaching of calcium, however, this has not been observed (Iies and Dosmann 1999). Many shade trees originate in forests where decomposition and incorporation of organic matter cause pH to fluctuate below 7 (Ware 1990). Hence, soil acidification resulting from the decomposition of organic mulches may provide urban trees with a beneficial environment for development.

Summing up, the benefits of mulch appear to outweigh the drawbacks. Improper application of mulch may affect soil aeration and low spring soil temperature may delay the onset of roots. Furthermore, photosynthesis and gas exchange may be reduced due to high air temperature and vapour pressure deficits which exist above mulch. However, the prevention of extreme soil temperature during the hot summer months, in combination with adequate soil moisture, and favourable pH creates an environment in which tree growth and development is not impeded. Taken together, these benefits lead to the observed improvements in above- and below-ground growth associated with mulch application (Greenly and Rakow 1995; Samyn and De Vos 2002; Watson 1988).

2.2.4 Summary of Surface Cover Types

The different surface cover types provide various benefits and drawbacks to urban tree development. One factor which stands out as being crucial for success is adequate soil moisture, which both pavements and mulch provide (Iies and Dosmann 1999; Whitlow et al. 1992). Turf, on the other hand, competes with trees for soil moisture and contributes to its depletion through evapotranspiration (Coll et al. 2004). Another important factor is soil temperature, which for optimal root function should remain between 10-30°C (Ruark et al. 1983). Soil temperature beneath pavements can often exceed this threshold (Celestian and Martin 2004), while mulch's buffering effect maintains cooler soil temperatures (Iies and Dosmann 1999). Air temperature is higher above mulch and pavement than it is above turf (Montague and Kjelgren

2004), due in part to evapotranspirational cooling, which affects relative humidity and the vapour pressure deficit between leaves and the atmosphere. Higher vapour pressure deficit results in stomatal closure leading to reduced gas exchange and photosynthesis (Turner et al. 1984). Finally, soil compaction, typical of paved sites, can severely impact tree growth (Smiley et al. 2006) by precluding root expansion (Sinnett et al. 2008) and reducing gas diffusion, thereby affecting root respiration (Kozlowski 1999).

Knowledge of how other surface types affect tree development provides insight into the factors necessary for successful growth and survival. If porous paving is to facilitate tree growth in urban areas, it will have to provide adequate soil moisture and aeration, while maintaining soil and air temperatures within thresholds for optimal root and shoot development. Finally, the pavement profile design will likely have to limit soil compaction such that growth and physiology is not hindered.

2.3 Hypotheses

Clearly, additional research is necessary to explore the relationship between porous paving and tree growth and survival, as prior research on the topic is lacking. The direct effect of porous paving on trees has never been explored. And while the indirect evidence obtained in other studies showing the effect of porous paving on physical soil conditions is encouraging, it is inadequate as these studies did not incorporate trees. Since trees alter their environment through shading, transpiration, and soil moisture uptake, the conclusions from previous studies cannot be guaranteed in a treed environment.

In order to fully understand the relationship between porous pavements and urban trees, it is imperative to experimentally derive if, and why, tree development is affected by overlying porous pavement. Additionally, understanding how porous paving affects the factors known to impact tree development such as soil moisture, aeration, as well as, soil and air temperature, and soil compaction will provide a basis for evaluating the suitability of porous pavement for use around urban trees. The existing gap in the literature will be addressed by conducting a field experiment that tests the effect of porous pavements, using different profile designs, on underlying soil physics and chemistry, as well as, resulting above- and below-ground tree growth.

Chapter III

Study Site and Methodologies

3.1 Study Site

To test the hypotheses that pavement type and profile design affect soil physics and chemistry, and subsequently tree growth, an experiment was designed and installed on city council land in Harewood, Christchurch (Lat: -43.493, Long: 172.437), the largest city in New Zealand's South Island. The top metre of soil is a fine sandy loam (Raeside 1974) overlying a deposit of sand and gravel, a remnant of the alluvial outwash deposited by an ancient glacier (Brown and Weeber 1992).

The temperate climate experiences mean daily maximum temperatures ranging from c. 10°C in July to 21°C in January (McGann 1983). Occasional 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 600-700mm annually and is generally evenly distributed throughout the year, with a tendency for slightly higher early winter precipitation (McGann 1983).

3.2 Site Preparation and Experimental Design

In July 2007, prior to installing porous and impervious paving on site, the soil was cultivated to remove the existing turf and ensure uniform physical conditions to 30cm depth. The resulting mean sampled bulk density of this upper layer was 1.26Mg/m^3. Given this density and an estimated particle density for sandy loam of 2.65Mg/m^3 (Hillel 1998a), the approximate total porosity of the uppermost 30cm of soil is 52.5%.

Following site preparation, treatments were installed in an augmented factorial design consisting of controls and four treatments; treatments were split evenly amongst plots, such that ten replicates existed per treatment . The pavement treatments, measuring 2.3m by 2.3m (with a 30cm diameter circular cutout in the centre), were based on the combination of pavement type (2 levels: porous, impervious) and pavement profile design (2 levels: +/- subgrade compaction and gravel base). The resulting four treatments were impervious concrete pavement (IP), impervious concrete pavement with compacted subgrade and gravel base (IP+), porous concrete pavement (PP), and porous concrete pavement with compacted subgrade and gravel base (PP+). The distinction between the two levels of pavement profile design is related to the preparation of the profile below the pavement surface course. In IP and PP plots, profile preparation was limited to levelling the topsoil with a 500kg roller. In contrast, in IP+ and PP+ plots, topsoil was removed to a depth of 20cm, exposing the parent material which we termed the subgrade. Then, a 20cm deep base layer of washed, uniformly graded, 20-40mm gravel was placed in the hole, overlaying the subgrade. Finally, the plots were levelled with a 500kg roller.

The difference between the two levels of pavement profile design are thus related to the inclusion (or exclusion) of a gravel base and the soil strength of the subgrade. Soil strength was measured via a soil compaction meter (Spectrum Technologies, Inc., Plainfield IL) in accordance with ASAE Standard EP542 (2002). Mean values, which differed significantly amongst treatments ($p<0.001$), were 892 kPa, 874 kPa, 808 kPa, 2458 kPa, and 2363 kPa for control, IP, PP, IP+ and PP+ respectively. Finally, IP and IP+ plots were overlaid by a standard impervious concrete, while PP and PP+ were overlaid by a pervious concrete designed specifically for this experiment.

The porous concrete pavement used in the experiment was provided by a contractor (Firth Industries, Christchurch) who prepared, then poured 11m^3 of ready-mixed porous concrete on site. The mix design was specified to achieve 30% porosity and comprised 1523kg of 6mm angular aggregate, 243kg Portland cement, and 50kg water per cubic metre. Samples of the fresh concrete were taken to determine if the provided PP met mix design specifications for porosity and hydraulic conductivity. Instead of a porosity of 30% as specified, the PP treatments had only 11% porosity. Though under specification, the lower porosity did not likely impede precipitation infiltration (de Solominihac et al. 2007). Higher porosity is desirable when clogging is expected. However, as this is an experimental site and is not subjected to traffic or sediment runoff, clogging was not believed to be an issue, and therefore, neither was the relatively low porosity. Also, the measured hydraulic conductivity of 1.04cm/s in the samples exceeds local standards for porous pavement permeability (ACC 2003).

Subsequent to treatment installation, 50 one-year old, bare-root oriental plane (*Platanus orientalis*) seedlings were randomly assigned to plots. Seedlings were raised from seeds collected from a single parent tree of Australian provenance (Appletons Tree Nursery Ltd., Nelson, New Zealand). Herbicide applications were used, as necessary, to limit weed competition in control plots, which were characterised by an exposed soil surface. Seedlings were planted in early August 2007 in undisturbed soil in plot centers and, in the case of treated trees, surrounded by concrete pavement pads, which had been installed in early July 2007. A schematic of the plot designs is provided in figure 3.1.

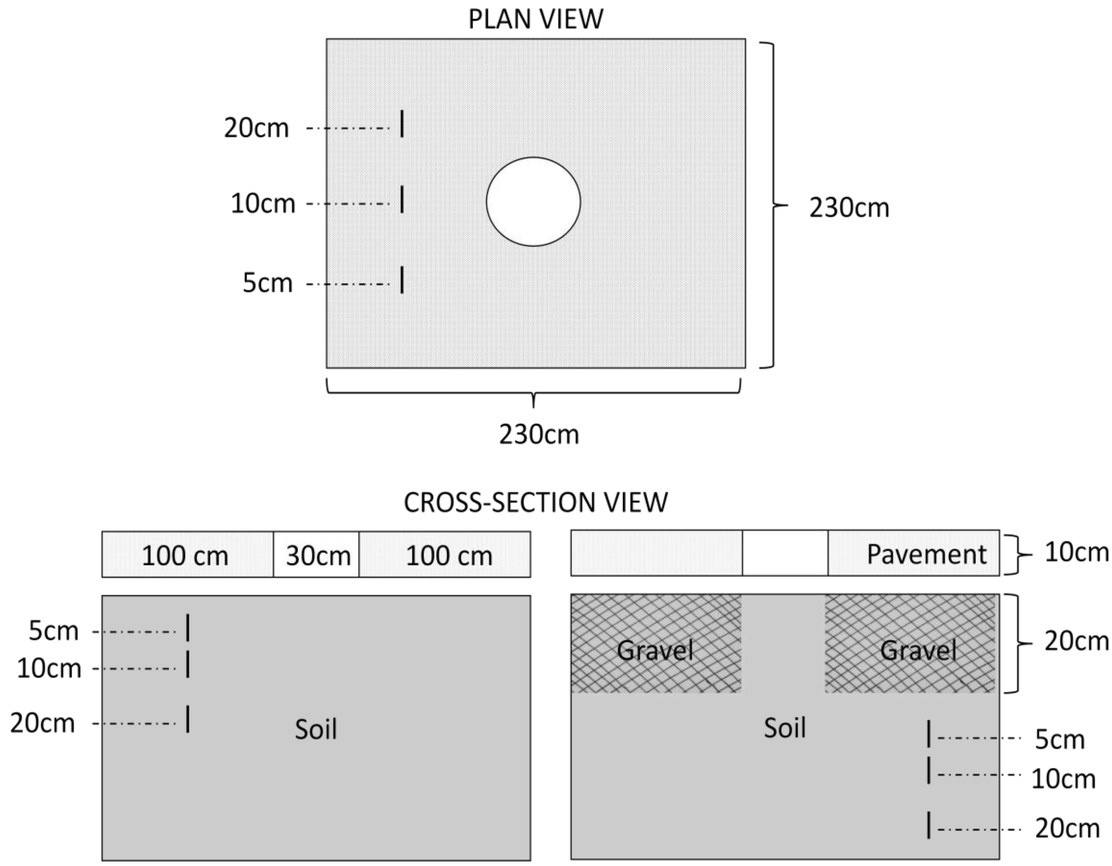


Figure 3.1. Plan and cross-sectional view of plot designs for pavement treatments with and without a gravel subbase. Soil moisture sensors are located at 5 cm, 10 cm, or 20 cm beneath the pavement, or gravel depending on the treatment.

The experiment remained in place for two full growing seasons. During the second week March 2009, concrete pads and gravel were removed in order to study underlying soil characteristics and root distribution. To comprehensively measure the treatment effect on the surrounding environment, physical and chemical soil characteristics were measured and contrasted. The soil environment was characterised by measuring soil moisture and soil aeration, strength, reaction, as well as micro- and macro-nutrient concentrations (calcium, magnesium, potassium, sodium, iron, and aluminium). Tree response to these conditions was gauged by measuring development and functional attributes including height and diameter increment, root distribution, above- and below-ground biomass, and leaf nutrient status. Specific details of data collection and statistical analysis are provided in each of the subsequent results chapters.

Plate 3.1. Aerial photo of experiment site in January 2009.

Chapter IV

Variation in Soil Moisture and Aeration Resulting from Pavement Porosity and Design

The contents of this chapter have been published as:

Morgenroth, J. and G.D. Buchan. 2009. *Soil Moisture and Aeration Beneath Pervious and Impervious Pavements*. Arboriculture and Urban Forestry. 35(3): 135-141.

4.1 Introduction

Urban areas are characterised by a high concentration of impermeable surfaces; pavements are most pervasive, covering more than half of all land in highly-developed urban areas (Ferguson 2005). A recent paradigm shift has resulted in the proliferation of porous pavements. This is especially true in the United States where the Clean Water Act and other regulations enforced by the Environmental Protection Agency necessitated new methods for stormwater management. These regulations require decreasing surface runoff and treating water at the source, both of which are achieved by porous pavements.

Though porous paving is proliferating, research detailing its impact on the surrounding environment is lacking. A number of untested theories are liberally quoted in the literature concerning the direct impact of porous paving on the underlying soil environment, and its indirect effect on urban trees. Tennis et al. (2004) conclude that porous pavement is “ideal for protecting trees in a paved environment” and Ferguson (2005) suggests that it can “increase the longevity of trees by improving moisture and oxygen relations”. Though these sources provide no experimental evidence, their assumptions appear logical as normal tree growth and function require adequate soil water and aeration (Larcher 2003), both of which are allegedly enhanced by porous pavements.

While the overall aim of the thesis is to better understand the relationship between porous paving, soil physical conditions, and tree growth, the data presented in this chapter are limited to the effects of overlying porous pavement on underlying soil. It is expected that the permeability of porous paving, relative to impervious paving, will result in differing soil moisture and aeration dynamics.

4.2 Methods

4.2.1 Data collection

Soil volumetric moisture content (θ_{soil}) was measured every five minutes from December 2007-March 2009 using ECH_2O EC-20 probes (Decagon Devices, Inc.) interfaced with a Campbell CR10X data logger (Campbell Scientific, Inc.). Following previous authors (e.g. Baumhardt et al. 2000; Lane and Mackenzie 2001), rather than using the ECH_2O probe's built-in calibration, the following soil-specific calibration was obtained, using methods recommended by the manufacturer (Cobos 2007):

$$\theta_{soil} = 1.2447 \cdot \theta_{probe} + 3.5422 \qquad \text{(Equation 4.1)}$$

Here θ_{soil} (%) is the calibration-adjusted soil water content, and θ_{probe} (%) is the value predicted by the ECH_2O probe. By post-processing the data with this calibration, the accuracy of θ_{soil} is assured to ±2% (Decagon Devices Inc. 2006).

In half the plots, three probes were buried 5 cm, 10 cm, and 20 cm beneath the soil surface halfway between the seedling and the plot edge (75 probes in total). Each sensor was inserted parallel to the soil surface, with its flat surface vertical to minimise disturbance of soil moisture movement. The probes were installed in July 2007 and the first readings were collected in December 2007 to allow sufficient time for equilibration.

Four probes malfunctioned temporarily, during which time their readings were discarded. The readings from the remaining four probes, per treatment and depth combination, were used to calculate an average θ_{soil} for that combination. Furthermore, an electrical fault caused data to be lost during a month-long period spanning May - June 2008.

The permanent wilting point (PWP) and field capacity (FC) of the soil were measured via pressure plate (Model 1500 15 bar ceramic plate extractor, Soil Moisture

Equipment Corp., Santa Barbara, CA) and a soil moisture release curve was also determined. Their values are 11.1% and 27.9% respectively, by volume.

Aeration was determined using the steel rod technique (Carnell and Anderson 1986). The effectiveness and efficiency of the technique was tested on a subsample of plots prior to accepting the method as a whole (Appendix C). Following successful testing, two separate measurement periods were staged coinciding with spring and summer seasons. Time period 1 (hereafter referred to as spring) ran from 3 September 2008 – 3 December 2008, and time period 2 (hereafter referred to as summer) from 4 December 2008 – 5 March 2009. During each of these measurement periods, 50 steel rods were allocated evenly amongst all treatments and inserted into soils of all plots following the method of Hodge et al. (1993). Rods were inserted halfway between the centre and edge of each plot. After approximately three months in the soil, all rods were unearthed, cleaned, and swabbed in an ammonia solution to stop further oxidation. Following Carnell and Anderson (1986), two corrosion categories were created: 1) red/brown rust or raised black corrosion, which indicated well aerated soil; and 2) smooth black or matte grey corrosion indicative of anaerobic conditions, or shiny metal, both classed as inhospitable for root growth (Plate 4.1). Using these categories, the corrosion patterns were analysed and scores reflecting the proportion of rust were assigned to each 12 cm segment of rod based on the method of Hodge and Boswell (1993).

Plate 4.1. Steel rods showing different corrosion patterns. An unused, shiny rod (bottom) is contrast with a rod unearthed from a poorly-aerated soil (middle) and a well-aerated soil (top).

4.2.2 Statistical Analyses

Mean weekly soil moisture data and seasonal aeration data were compared via one-way analysis of variance (ANOVA) using orthogonal, *a priori*, single degree-of-freedom contrasts to examine treatment effects, as well as, interactions of interest (Marini 2003). Contrasts were as follows:

1. Control v. 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 X pavement type.

All statistical differences are reported at p-value = 0.05. Analyses were undertaken using the R statistical package, version 2.8.1 (R Development Core Team 2008).

4.3 Results

4.3.1 Soil Moisture Overview

Mean soil moisture in the uppermost 20 cm of soil, calculated as the mean of measured soil moisture at 5 cm, 10 cm, and 20 cm, is presented in Figure 4.1 (mean θ_{soil} for each soil depth are available in Appendix A). Convergence and divergence of θ_{soil} in control plots and beneath the four pavement treatments appears cyclical, likely responding to seasonal factors such as precipitation, evaporation, temperature, and relative humidity, amongst others.

Soil moisture in control plots was most variable, increasing with precipitation and decreasing afterwards. Steady increases in θ_{soil} appear to be associated with periods of low, but sustained rainfall, whereas acute increases in θ_{soil} follow large rainfall events. The magnitude of soil moisture increase depended on the θ_{soil} prior to the rainfall event. If soil had been relatively dry, the magnitude of increase was greater (i.e. weeks 9, 10, and 63), whereas if soil had been relatively wet, the magnitude of increase was smaller (i.e. week 33). Predictably, θ_{soil} was highest during the winter months (35.9% in week 37) and lowest during both summer periods (24.3% in week 15 and 18.1% in week 61).

The θ_{soil} dynamics beneath porous and impervious pavement profiles designed with a compacted subgrade and gravel base (PP+ and IP+) generally followed those in control plots, with seasonal θ_{soil} minima and maxima occurring during roughly the same time periods. Throughout the first summer, mean θ_{soil} dipped to 23.7% (week 16) and 24.5% (week 17) for PP+ and IP+ respectively, while during the second summer θ_{soil} beneath these same treatments decreased to 17.8% and 19.2% during week 61 (Figure 4.1). Conversely, mid-winter θ_{soil} reached 35% for PP+ (week 34) and 34.2% for IP+ (week 38).

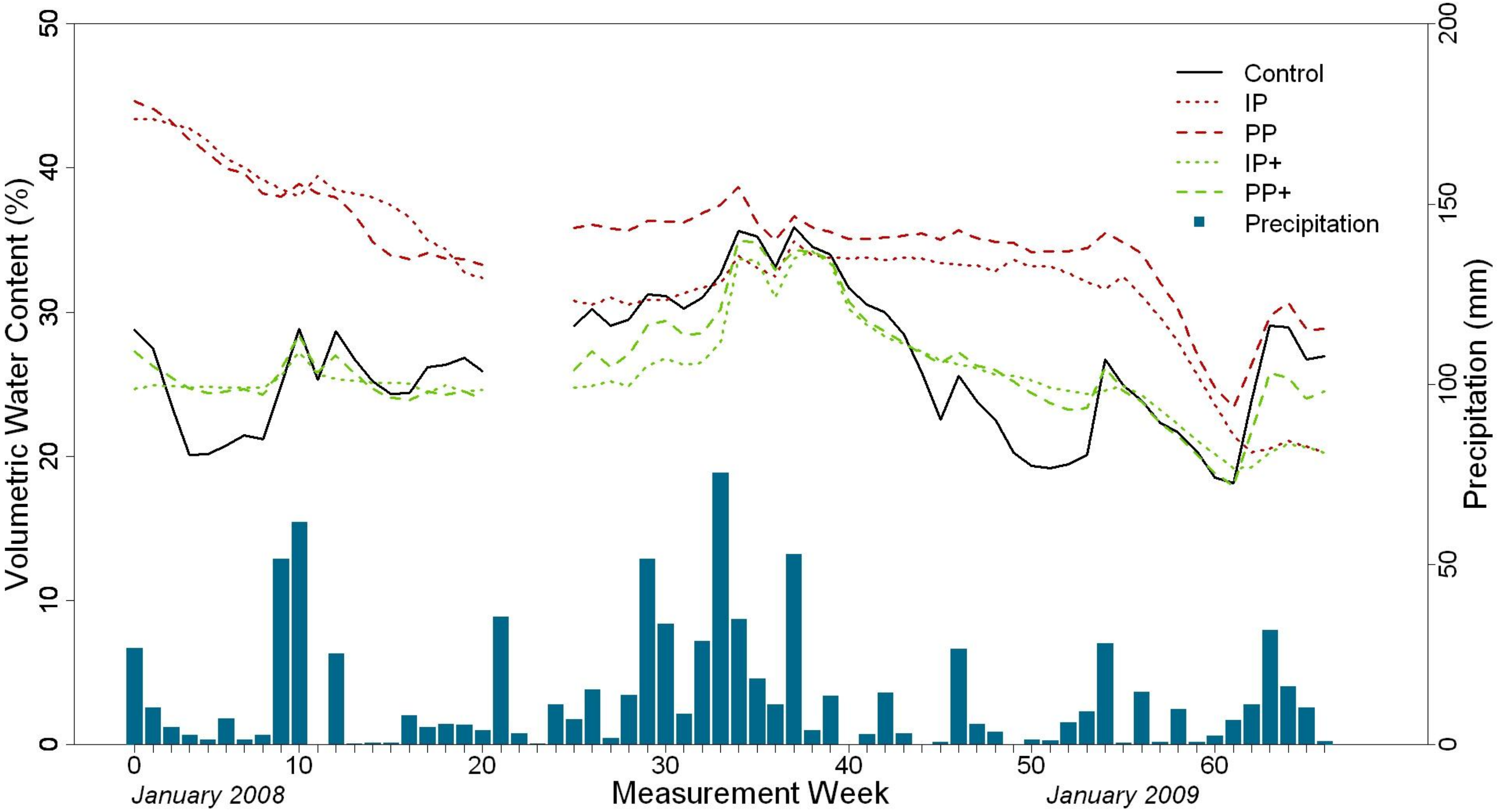


Figure 4.1. Variations of a) mean weekly soil moisture in the uppermost 20 cm of soil, and b) total weekly precipitation.

Soil moisture in pavement profiles designed without a compacted subgrade and gravel base (PP and IP) was highest during the first week of measurement, with values of 44.6% and 43.4% for PP and IP plots respectively (Figure 4.1). It decreased progressively throughout summer and autumn reaching a low of 33.6% for PP (week 20) and 30.5% for IP (week 26). With increasing precipitation during the winter of 2008, a steady increase in θ_{soil} occurred beneath both treatments, prompting soil moisture values of 38.7% beneath PP (week 34) and 34.9% beneath IP in week 37. Soil moisture remained virtually unchanged for 18 weeks before dropping sharply in late December 2008. Seasonal lows were reached by mid-summer, declining to 23.1% (week 61) and 20.3% (week 62) for PP and IP respectively.

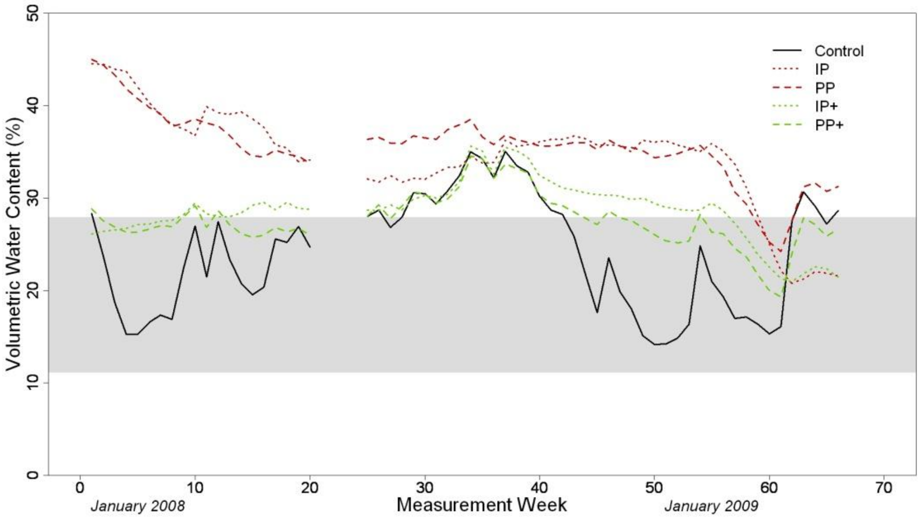
Generally, soil moisture in control plots remained between the permanent wilting point (11.1%) and field capacity (27.9%) (Figure 4.2). Beneath pavement, dips in θ_{soil} to values nearing the PWP were rare. The lowest θ_{soil} value measured beneath any pavement treatment was 16.3% (beneath PP+ at 20 cm in week 61). In comparison, soil moisture in control plots decreased to levels nearing the PWP more frequently and could remain dry for weeks at a time (e.g. weeks 3-8, 47-53, and 56-61). The lowest θ_{soil} value in control plots was 14.2%, which occurred during weeks 50 and 51. These low θ_{soil} values were only characteristic at 5 cm depth; at 10 cm and 20 cm depth, θ_{soil} was always comfortably above the PWP. Following large precipitation events (e.g. week 10) or during the wet winter months (weeks 25-43), soil moisture in control plots could temporarily exceed field capacity. Likewise, soil moisture in IP+ and PP+ plots was greater than field capacity only during the wet winter months (weeks 29-42), but unlike control plots, did not increase above field capacity following large precipitation events. In contrast, soil moisture in IP and PP plots was consistently above field capacity. Only during weeks 59-63 was soil moisture lower than field capacity, a period corresponding with late summer.

The following three sections detail the results of pre-planned orthogonal contrasts by highlight significant treatment differences, which were dependent on soil depth and time of year. The interaction between pavement type and profile design, never proved significant (Appendix A, Table A7). This suggests that the response of soil moisture within a given profile design did not differ between pavement types, or vice versa.

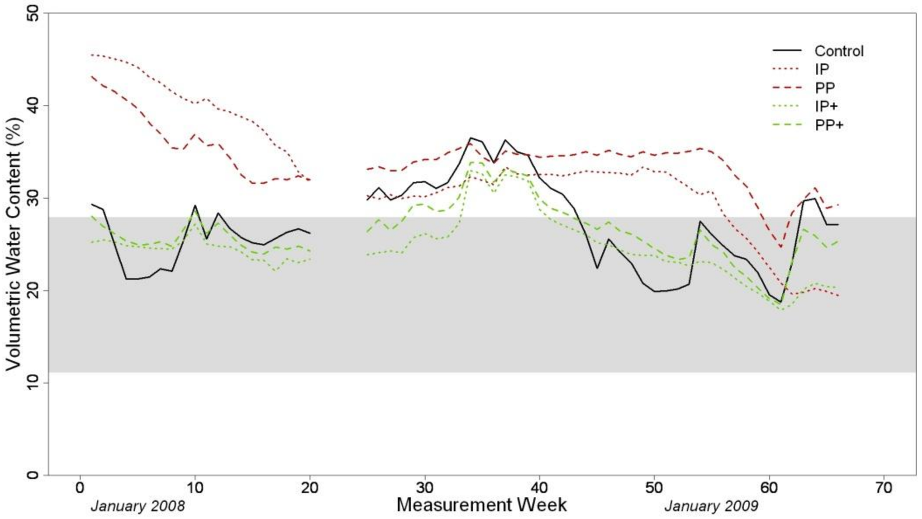
4.3.2 Effect of Pavement on Underlying Soil Moisture

This section compares the dynamics of the mean soil water content of the control plots with that of the pooled mean of all paved plots. During the winter months, soil moisture was comparable between control plots and the pooled mean of all paved plots. However, during late spring, summer, and early autumn soil moisture contrasts were significant for different lengths of time depending on soil depth (Table A4). The duration of pavement effects declined with increasing soil depth; significant differences occurred for 40 weeks at 5 cm depth, 22 weeks at 10 cm depth, and only 5 weeks at 20 cm depth. During weeks 1-18, 27, and again from 41-60, soil moisture beneath pavements exceeded that in control plots at 5 cm depth (Figure 4.2a). Differences in θ_{soil} still existed at 10 cm, however the duration of these periods of significance were shorter, spanning weeks 3-8, 35, 37, 44-53, and 63-66 (Figure 4.2b). At this depth, θ_{soil} was generally greater beneath paved treatments, but this was not always the case (i.e. weeks 35, 37, and 63-66). Deeper still, at 20 cm soil depth, θ_{soil} beneath control and paved plots differed significantly very rarely (weeks 4, 5, 50, 51, and 64) (Figure 4.2c). In all but week 64, θ_{soil} was greater beneath pavements than in control plots.

a)



b)



c)

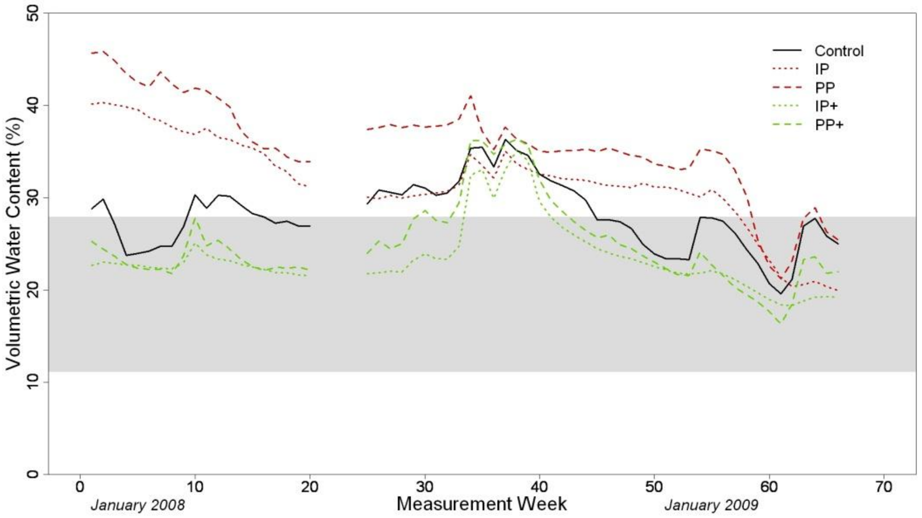


Figure 4.2. Mean soil volumetric water content at a) 5 cm, b) 10 cm, and c) 20 cm depth for all treatments. The shaded region represents the least-limiting water range between the field capacity and the permanent wilting point.

4.3.3 Effect of Pavement Profile Design on Underlying Soil Moisture

The effect of including structural elements (compacted subgrade and gravel base) in the pavement profile design was prevalent, at all depths, for a majority of the measurement period (Table A5). Unlike contrast 1, which exhibited marked differences with soil depth, contrast 2 was generally independent of depth (Figure 4.2). Soil moisture was significantly lower beneath plots whose design incorporated structural elements during weeks 1-33 and 40-57 (5 cm depth); 1-33 and 40-60 (10 cm depth); and 1-33 and 40-59 (20 cm depth). The duration of significance for contrast 2 represents a great majority of the measurement period. Seemingly, contrast 2 was only insignificant during periods of persistent rainfall, such as late winter and early spring of 2008 (weeks 33-40). During these times, there was no significant difference in θ_{soil} between plots including or excluding structural elements in the pavement profile design.

4.3.4 Effect of Pavement Type on Underlying Soil Moisture

Due to the open nature of porous paving, it was expected that underlying soil moisture would differ compared with impervious pavements. However, this was not always observed. In fact, soil moisture was statistically similar beneath both pavement types for 50 of the 66 measurement weeks (Table A6). Nevertheless, a significant pavement type effect was present during particular weeks and interestingly, the incidence and duration of the effect increased with soil depth. Significant differences occurred for only 4 weeks at 5 cm depth, but 13 weeks at 10 cm depth, and 16 weeks at 20 cm depth. At 5 cm depth, porous pavement resulted in greater underlying soil moisture than impervious pavement during the final 4 weeks of measurement (weeks 63-66) (Figure 4.2a). At 10 cm depth, θ_{soil} beneath porous pavement was greater than beneath impervious pavements during weeks 26, 28-33, 54, and 62-66 (Figure 4.2b). The duration of a pavement type effect increased again at 20 cm soil depth, where soil moisture beneath porous paving was greater than beneath impervious paving during weeks 26, 28-33, 35-37, 40, 41, and 63-66 (Figure 4.2c).

4.3.5 Soil Moisture Response to Precipitation

The magnitude of daily θ_{soil} fluctuations depended on treatment. Unpaved soils exhibited highly variable θ_{soil}, whereas fluctuations beneath paving were less pronounced. An illustrative example is presented for weeks 61-63 (Figure 4.3), where soil moisture in control plots increased sharply in response to precipitation events; mean θ_{soil} increased 11% for control plots during these three weeks. Soil moisture beneath porous paving also exhibited a distinct response to precipitation events, albeit a more tempered one. Increases of 6.5% and 7.8% were measured for PP and PP+ plots 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 IP+ plots and actually decreased by 0.9% for IP, during the same time period. It certainly appears that impervious pavement cover buffers underlying soil from acute increases of soil moisture resulting from precipitation. Soil moisture loss was also less marked in paved plots. Unpaved sites were subject to water loss through evapotranspiration and drainage, while pavement protected soils from evaporation losses (Appendix B), leaving only transpiration and drainage as mechanisms for water loss.

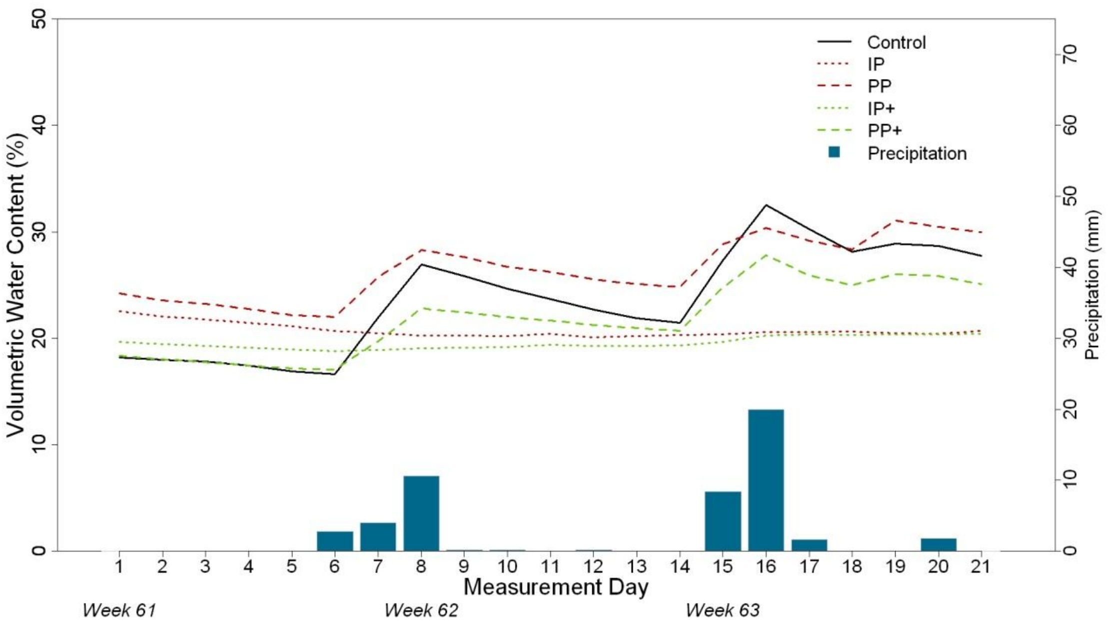


Figure 4.3. Daily response of soil moisture (average of 5cm, 10cm, and 20cm values) to precipitation during weeks 61-63.

4.3.6 Effect of Pavements on Soil Aeration

Aeration data showed contrasting results, dependent on the season during which measurements were taken. Differences in soil aeration between spring and summer were evident with higher anaerobic scores occurring during the wetter spring months (Figure 4.4).

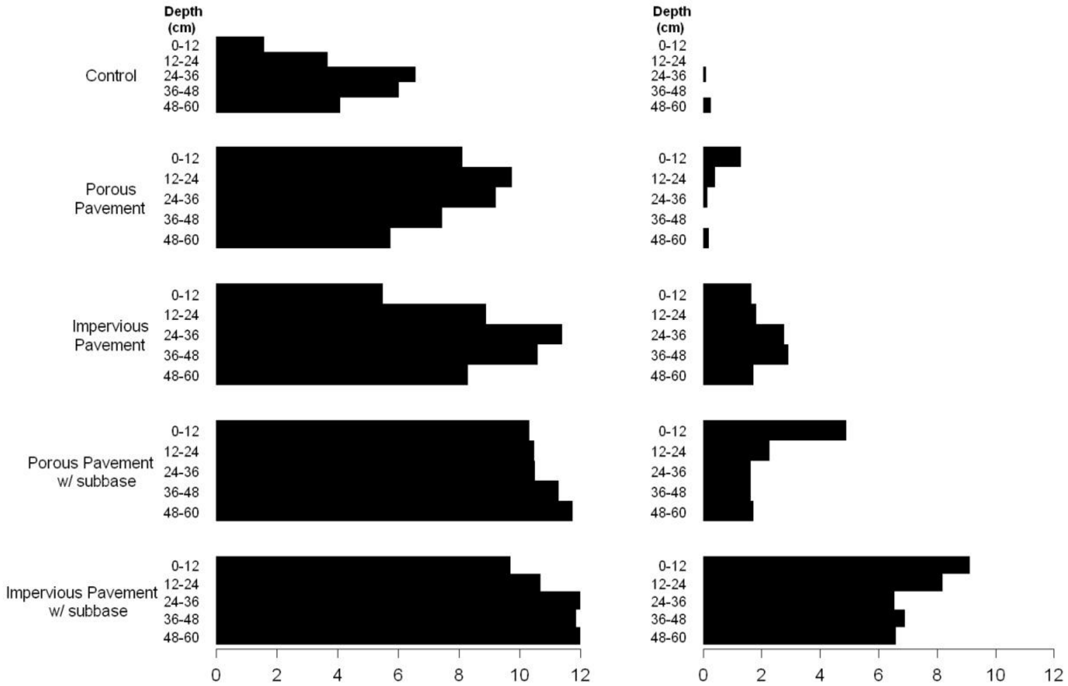


Figure 4.4. Evaluation of soil aeration. The mean anaerobic score for all treatments stratified by depth beneath the soil surface. Greater anaerobic score corresponds to decreased soil oxygen. Plots correspond to spring 2008 (*left*) and summer 2008-2009 (*right*).

Within each season, differences in soil aeration occurred as a result of treatment. During spring, anaerobic scores were distinctly lower in unpaved soils than in paved soils at all depths (Table 4.1, contrast 1). Pavement profile design had a significant impact with greater aeration (lower anaerobic scores) occurring in IP and PP plots relative to IP+ and PP+ plots in the uppermost 12cm of soil and again from 36-60cm depth (Table 4.1, contrast 2). Deep in the soil profile, from 36-60cm, impervious pavement had greater anaerobic scores (lower aeration) than porous pavements, however large variation negated any statistical significant effect of pavement type

(Table 4.1, contrast 3). Aeration was not influenced by an interaction effect between pavement type and profile design (Table 4.1, contrast 4).

Table 4.1. Single degree-of-freedom contrasts comparing the effect of pavement type and profile design on spring soil aeration. Values presented are p-values for indicated soil depth. * $p < 0.05$

Contrast	$p_{0\text{-}12}$	$p_{12\text{-}24}$	$p_{24\text{-}36}$	$p_{36\text{-}48}$	$p_{48\text{-}60}$
1. Control vs. all other treatments	1.12E-07*	3.06E-06*	1.14E-03*	2.75E-03*	9.93E-04*
2. Main effect (pavement profile design)	1.85E-03*	0.24	0.39	0.04*	8.62E-04*
3. Main effect (pavement type)	0.10	0.76	0.10	0.13	0.31
4. Interaction (pavement profile design x pavement type)	0.31	0.62	0.76	0.29	0.40

During the summer months, control plots again had lower anaerobic scores than the pooled mean of pavement treatments (Table 4.2, contrast 1). While both main effects were significant at all depths, a significant interaction effect was evident in the uppermost 24 cm of soil (Table 4.2, contrast 4). Here, porous pavement was associated with lower anaerobic scores, but only when the pavement profile was designed to incorporate a compacted subgrade and gravel base. In deeper soil, pavement profile design had a significant effect on anaerobic score, with greater values (lower aeration) occurring in pavements designed to incorporate a compacted subgrade and gravel base (Table 4.2, contrast 2). Finally, pavement type significantly affected soil aeration during summer, whereby both PP and PP+ plots resulted in lower anaerobic scores than IP and IP+ plots from 24-60cm depth (Table 4.2, contrast 3).

Table 4.2. Single degree-of-freedom contrasts comparing the effect of pavement type and profile design on summer soil aeration**.** Values presented are p-values for indicated soil depth.* $p < 0.05$

Contrast	$p_{0\text{-}12}$	$p_{12\text{-}24}$	$p_{24\text{-}36}$	$p_{36\text{-}48}$	$p_{48\text{-}60}$
1. Control vs. all other treatments	4.92E-05*	2.20E-03*	2.00E-02*	7.40E-03*	3.79E-02*
2. Main effect (pavement profile design)	6.69E-08*	3.21E-05*	0.01*	3.90E-03*	1.85E-03*
3. Main effect (pavement type)	0.01*	1.57E-04*	6.72E-04*	5.89E-05*	1.87E-03*
4. Interaction (pavement profile design x pavement type)	0.03*	0.01*	0.27	0.21	0.09

4.4 Discussion

4.4.1 Effect of Pavement on Underlying Soil Moisture

Soil moisture was generally greater beneath pavements (Table A4), supporting the results of other researchers (e.g. Wagar and Franklin 1994) who have shown that soil moisture beneath pavements generally exceeds that in adjacent, unpaved soil. Two compounding mechanisms likely result in paved soils exhibiting higher θ_{soil} than unpaved soils. The first is a distillation process, whereby vapour diffuses towards, then condenses on, a cool surface. Soils gain heat energy and reach their maximum temperature later than maximum air temperature, with a delay between c. 1 hour at the surface to c. 10 hours at 30 cm depth (Buchan 2001; Celestian and Martin 2004). Following this, in the ‘heat release’ half of the diurnal cycle, they release heat back into the atmosphere. In the early evening, as 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 barrier to block moisture migration, and 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 characterise 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. This was confirmed in an evaporation test described in Appendix B. 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 gradient, whereby relatively low soil moisture 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.

4.4.2 Effect of Pavement Profile Design on Underlying Soil Moisture

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 distillation is limited by the inclusion of a gravel base. The relative effect of distillation between plots with and without a gravel base is illustrated by the soil moisture dynamics following the winter rains (week 37) (Figure 4.1). From this point, mean θ_{soil} in plots with gravel bases drops from 34.3% to 24.4% (PP+) and 33.7% to 24.9% (IP+) by week 55. This represents a decrease of 9.9% for PP+ and 8.8% for IP+. During this same period θ_{soil} in plots without a gravel base decreased from 36.6% to 34.7% in PP (1.9% decrease) and 34.9% to 32.5% in IP (2.4% decrease). Clearly, during this 18 week period, soil moisture decreased at a much greater rate in plots with a gravel base. It is inferred that the inclusion of a gravel base limits distillation and thus, results in significantly lower soil moisture. Without a distillation effect to replenish water in the surface soil, θ_{soil} is inevitably lower in plots designed to incorporate a gravel base.

There was a brief period (weeks 34-39) during which contrast 2 was insignificant. During these 6 weeks, θ_{soil} was similar in all treatments, hovering well above field capacity. It is likely that the heavy and continuous rainfall during this time period precluded any distillation effect, thereby resulting in insignificant differences in contrast 2.

4.4.3 Effect of Pavement Type on Underlying Soil Moisture

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 (near-saturated) soil moisture 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 may not have the ability to retain additional water, thus 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.

Week 61 is crucial for illustrating this point (Figure 4.1). Following nearly a complete summer of intermittent precipitation, soil moisture had fallen to experimental lows for all treatments by week 61. Then, several weeks of consistent rainfall saw an acute increase in θ_{soil} by week 63 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 (Figure 4.3). The result was a significant pavement type effect during weeks 62-66.

Could the same explanation be used for the other period of significant differences between porous and impervious pavement, namely weeks 26-42? Unfortunately, the missing data in weeks 21-25 prevents reaching a definitive conclusion. However, the period leading up to this period of significance, and the aftermath, bear a resemblance to week 61. By week 21, all treatments were in steady decline in late summer and early autumn (Figure 4.1). Then, heavy rainfall occurred and by week 26 the θ_{soil} beneath both porous treatments had increased (by 2% for PP and 1.5% for PP+), whereas the impervious treatments increased only slightly (by 0.3% for IP+), or even decreased by 2% (IP). Though the magnitudes of increase or decrease differ from those following week 61, the relative difference between porous and impervious pavements is similar. If this inference is correct, it would also explain why soil moisture was greater beneath porous pavements during many periods from weeks from 26-42. Furthermore, it would help confirm the theory that soil moisture differences attributable to pavement type occur due to rapid infiltration of precipitation via porous pavements, but only when underlying soil moisture is relatively low.

4.4.4 Effect of Pavements on Soil Aeration

Comparisons between anaerobic scores for spring and summer periods confirmed that poor aeration was more prevalent during the wet spring months than during the dry summer months. This is likely an indirect reflection of soil moisture content. Air and water contents follow an inverse relationship in soil pores; hence, high soil moisture implies low aeration, and vice-versa. Additionally, because oxygen diffuses through water c. 7500 times slower than through air (Feng et al. 2002), it is found at lower concentrations in wet soils. Thus, relatively poorer aeration of soils during the spring months is unsurprising as soil moisture during these months was greater than during summer months. Others have also reported seasonal differences in soil aeration and it is typical for lower aeration to occur during the wet spring months (Watson 2006).

Within each seasonal period, the data certainly support the observation that, relative to control plots, soil aeration is lower beneath pavements. However, the cause of this is unclear. Two potential explanations are offered here. Air diffusion into soil is likely to be impeded by pavements. Other authors have shown that this may be the case (D'Amato et al. 2002). If this were the case in this experiment, it would be expected that, due to its open structure, aeration beneath porous pavements would exceed that beneath impervious pavements. Though this was not the case during spring, it was during summer when both PP and PP+ plots had lower anaerobic scores than IP and IP+ plots at various soil depths. An alternative explanation for lower soil aeration beneath pavements is predicated upon the fact that pavements resulted in significantly higher soil moisture. Knowing that water and air are inversely related in soil pores, the lower degree of aeration beneath pavements is consistent with relatively higher soil moisture.

Differences related to pavement profile design were evident during both spring and summer with consistently lower aeration (greater anaerobic score) in IP+ and PP+

plots. This is likely a direct result of the compacted subgrade in these plots, which had mean soil strength of 2410 kPa, whereas soil in IP and PP plots had mean soil strength of only 841 kPa. Soil compaction reduces the pore space volume and, in doing so, favours water-filled, rather than air-filled pores. So, the smaller pores in the compacted subgrade of IP+ and PP+ plots are filled preferentially with water, resulting in low oxygen concentration and greater anaerobiosis.

As previously mentioned, pavement type resulted in differences in soil aeration only during the summer months. During this time, soil aeration beneath porous pavements was generally greater than beneath impervious pavements. Though the data identify this soil aeration difference beneath porous and impervious pavements, the explanation is uncertain. Given that soil moisture was equivalent beneath porous and impervious pavement for the great majority of this period, it is unlikely that any differences can be linked with soil moisture. Perhaps then, impervious pavements do, in fact, limit gas exchange between the atmosphere and the soil, whereas porous pavements allow for relatively greater gas diffusion.

4.5 Conclusion

This chapter highlights the complex nature of soil moisture and aeration dynamics in a paved environment. Depending on the pavement profile design and whether the pavement type is porous or impervious, there is the potential to significantly modify soil hydrology and aeration, relative to unpaved soil. This is of great importance to urban trees, as soil beneath the pavements forms the rhizosphere from which tree roots, along with soil microbes, obtain the water and nutrients necessary for growth and survival. So, with respect to tree requirements, soil in control plots is better aerated than soil beneath paved plots, however, relatively low θ_{soil} in control plots may limit water uptake by roots.

The effect of pavement type resulted in soil moisture and aeration beneath porous pavements occasionally being greater than beneath impervious pavements. This effect was tempered by season and differed with soil depth. Though soil moisture beneath porous pavement rarely differed from impervious pavement, short periods of relatively high soil moisture beneath porous pavements may still prove beneficial for tree growth. If porous pavement allows for a relatively rapid recharge of θ_{soil} during rainfall events, as seen following long periods without precipitation, then it may be beneficial for street trees facing drought stress. Moreover, given the importance of adequate soil aeration for root respiration, porous pavements may also contribute to greater tree growth by allowing for elevated soil aeration beneath porous pavement during the summer months.

Meanwhile, the effect of pavement profile design was considerable, altering both soil moisture and aeration. Paved plots designed to incorporate a compacted subgrade and gravel base (IP+ and PP+) had relatively lower soil moisture and aeration than paved plots without these structural elements (IP and PP), suggesting that they will be the worst environment for tree growth. Pavement profile design resulted in significant differences for a great majority of the 66 week experimental period, whereas pavement type resulted in differences during only 16 weeks. Because of the duration of the profile design effect, it is arguably more important than pavement porosity.

In summary, under the conditions of this experiment, the hypothesis that soil moisture and aeration differ beneath porous and impervious paving is supported, but depends on time of year and soil depth. Given temporary periods of increased soil moisture and aeration, it is plausible that porous pavements improve tree growth, as other authors have suggested.

Chapter V

Variation in Soil pH and Plant Nutrient Status as Influenced by Pavement Porosity and Design

5.1 Introduction

Soils are critical to plant growth, providing stability, as well as storing water and nutrients, both of which are necessary for physiological processes. Though urban soils are highly modified, their role remains the same. Despite high heterogeneity, layering, compaction, pollution, and pH extremes, urban soils support extensive and diverse plant life, including trees. Many urban soils are covered by impervious pavements, which can modify physical and chemical properties including soil moisture (Wagar and Franklin 1994) and temperature (Celestian and Martin 2004) generally promoting extremes. Though concrete pavements are not water soluble, calcium hydroxide, a major constituent of cement paste, is soluble in a variety of solutions including soft water, sea water, brine, and even weak inorganic or organic acids (Grattan-Bellew 1996). When reacting with water (H_2O) and carbon dioxide (CO_2), calcium hydroxide results in, amongst other products, exchangeable calcium ions (Ca^{2+}) (Grattan-Bellew 1996), which can raise the pH of the soil. By doing so, pavements can alter mineral availability to urban plants. Though mineral solubility varies drastically with changing pH, it is generally agreed that in alkaline soils, phosphorus (P), iron (Fe), manganese (Mn), and other micro-nutrients may not be available to plants (Larcher 2003), while in acidic soils, aluminium (Al) and Fe may be present at toxic levels (Sparks 2003). Thus, by affecting soil chemistry, pavements may affect the ability of plants to absorb nutrients, thereby limiting both growth and function.

Porous pavements may have an even more profound effect on soil chemistry than standard impervious pavements. Generally, more cement (from which Ca^{2+} is derived) is used to produce a given volume of porous pavement than an equivalent impervious pavement (Ferguson 2005). Also, the hydraulic conductivity of porous pavements is relatively high (Sansalone et al. 2008). So, as water infiltrates through the tortuous pores of the porous pavement, it may leach a greater quantity of calcium into 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. The aim of this experiment was to determine how porous and impervious pavements affect soil chemistry and subsequent plant uptake of nutrients. In particular, responses of soil pH and nutrient concentrations to treatment by porous and impervious pavements were tested. In addition, plant nutrient concentrations were contrasted to test whether changes resulting from pavement type subsequently affect plant nutrient uptake.

5.2 Methods

5.2.1 Data Collection

The concrete and gravel precluded access to underlying soils, so soil sampling was necessarily undertaken following completion of the experiment in March 2009. After concrete pads were removed, soil was collected for subsequent analysis. Four sub-samples per plot, collected from the uppermost 10cm soil by a soil corer, were bulked together such that a single composite sample could be analysed for each plot. Analysis undertaken by Lincoln University laboratories included pH, and ICP-OES (Inductively Coupled Plasma-Optical Emission Spectroscopy) to determine concentrations of calcium (Ca), potassium (K), magnesium (Mg), sodium (Na), Fe, and Al. Soil samples (0.7g) were digested in 5ml of concentrated nitric acid (HNO_3) and 5ml of hydrogen peroxide (H_2O_2) (30%), following similar methods to Sah and Miller (1992).

To complement soil reaction and nutrient analysis, plant leaf tissue analysis was conducted as a means of determining whether existing soil conditions contributed to plant nutrient deficiencies. For each tree, ten fully expanded leaves were selected from the upper half of the crown. These samples were collected in February 2009, washed with deionised water, then oven dried and ground. These prepared leaf samples (0.5g) were also sent to Lincoln University for acid digestion using the methods of Sah and Miller (1992). This was followed by ICP-OES analysis, which yielded leaf concentrations of Ca, K, Mg, Na, Fe, Al, P, cadmium (Cd), chromium (Cr), copper (Cu), Mn, sulfur (S), zinc (Zn), and nickel (Ni).

5.2.2 Statistical Analysis

One IP+ tree died between the first and second growing seasons and was excluded in all analyses. Soil pH, and soil and leaf nutrient concentrations were 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). Linear regressions were used to analyse relationships between soil and leaf nutrient concentrations, and soil pH. All significant differences are reported for $p < 0.05$. Analyses were performed using the R statistical package, version 2.8.1 (R Development Core Team 2008).

5.3 Results

Soil reaction ranged from moderately acidic (pH=5.61) to neutral (pH=6.89). Mean soil pH was 5.75 in control plots, 6.00 in IP, 6.26 in IP+, 6.35 in PP, and 6.58 in PP+ plots (Table 1). All pavement treatments significantly increased pH values to greater than found in control plots ($\bar{x} = 5.75$) (Table 2, contrast 1). Plots with a compacted subgrade and gravel base had higher mean pH than plots in which these were not incorporated in pavement design (Table 2, contrast 2). Meanwhile, porous pavements, regardless of profile design, increased pH relative to impervious pavements (Table 2, contrast 3). Soil reaction responded to both main treatment effects, but never their interaction (Table 2, contrast 4).

Relative to control plots, pavement treatments did not affect Ca or K concentrations, but they did have a significant effect on the concentrations of Na, Mg, Fe, and Al (Table 2, contrast 1). Decreased concentrations of Al, Fe, and Mg were evident between control plots and plots covered by pavements, whereas Na increased beneath pavements. Differences in soil nutrient concentrations were also evident amongst the four pavement treatments. Pavement profile design affected concentrations of Ca, Fe, Mg, and K, all four of which decreased below pavements designed to incorporate a compacted subgrade and gravel base (Table 2, contrast 2). Pavement type also affected soil nutrient concentrations (Table 2, contrast 3). Porous pavements decreased Al and Fe concentrations, but increased K and Na. The interaction between the two pavement factors was only significant for Na, where concentration decreased from IP to IP+ plots, but increased from PP to PP+ plots (Table 2, contrast 4).

Table 5.1. The effect of pavement type and profile design on soil reaction and nutrient concentration. Values shown represent means (1 standard error).

	Soil Reaction		**Soil Nutrient Concentration (mg kg^{-1})**					
Treatment	**pH**	**H+**	**Aluminium**	**Calcium**	**Iron**	**Magnesium**	**Potassium**	**Sodium**
Control	5.75 (0.03)	1.80e-06 (1.41e-07)	5.90 (0.4)	891.48 (32.43)	5.35 (0.37)	81.13 (2.57)	164.26 (9.26)	28.67 (2.04)
IP	6.00 (0.07)	1.10e-06 (1.48e-07)	3.91 (0.58)	918.35 (30.37)	4.28 (0.26)	80.87 (1.99)	184.22 (5.83)	35.85 (3.05)
PP	6.35 (0.05)	4.65e-07 (5.10e-08)	1.99 (0.38)	912.20 (27.56)	2.44 (0.33)	74.36 (1.71)	225.02 (8.75)	40.91 (2.66)
IP+	6.26 (0.03)	5.59e-07 (3.18e-07)	3.39 (0.35)	811.73 (43.24)	2.00 (0.24)	60.16 (2.46)	121.08 (5.48)	25.69 (1.41)
PP+	6.58 (0.06)	2.90e-07 (3.57e-08)	1.80 (0.52)	880.01 (33.99)	1.35 (0.26)	58.10 (3.10)	146.54 (4.96)	44.82 (3.34)

Table 5.2. p-values for single degree-of-freedom contrasts show differences in mean values for soil reaction (H+) and nutrient concentrations. * $p < 0.05$.

Contrasts	d.f.	p_{H+}	p_{Al}	p_{Ca}	p_{Fe}	p_{Mg}	p_{K}	p_{Na}
1. Control vs. All other treatments	1	4.32e-13*	5.12e-07*	0.77	1.60e-10*	2.57e-05*	0.54	0.01*
2. Main effect (pavement profile design)	1	0.001*	0.45	0.04*	1.87e-06*	2.13e-09*	2.39e-12*	0.25
3. Main effect (pavement type)	1	6.32e-15*	5.70e-04*	0.36	1.71e-04*	0.08	3.65e-05*	5.40e-05*
4. Interaction (pavement profile design x pavement type)	1	0.08	0.72	0.27	0.05	0.36	0.29	0.01

Soil reaction was significantly correlated with concentrations of nutrients in the soil, with the exception of calcium (Ca) and potassium (K). Regression analysis yielded significant linear relationships between soil pH and soil nutrient concentrations (Table 3), and suggested that sodium (Na) was positively correlated with pH, while magnesium (Mg), iron (Fe) and aluminium (Al) concentrations were negatively correlated (Figure 1).

Table 5.3. Regression coefficients of the linear functions of the form $y = a + bx$ where y represents the concentration (mg kg^{-1}) of each nutrient in soil, and x represents the soil pH value. * $p < 0.05$.

Nutrient	a	SE	b	SE	df	r^2	p
Calcium	1250.38	292.64	-59.08	47.27	43	0.04	0.22
Potassium	194.75	117.35	-4.06	18.96	43	0.05	0.83
Magnesium	230.51	25.64	-25.74	4.14	43	0.47	1.78e-07*
Sodium	-60.34	26.59	15.49	4.29	43	0.23	8.02e-04*
Iron	31.01	2.59	-4.51	0.42	41	0.74	1.54e-13*
Aluminium	36.83	2.86	-5.41	0.46	43	0.76	6.12e-15*

Abbreviations: SE, standard error; df, degrees of freedom; r^2, coefficient of determination; p, probability of predicted value equalling or exceeding observed value.

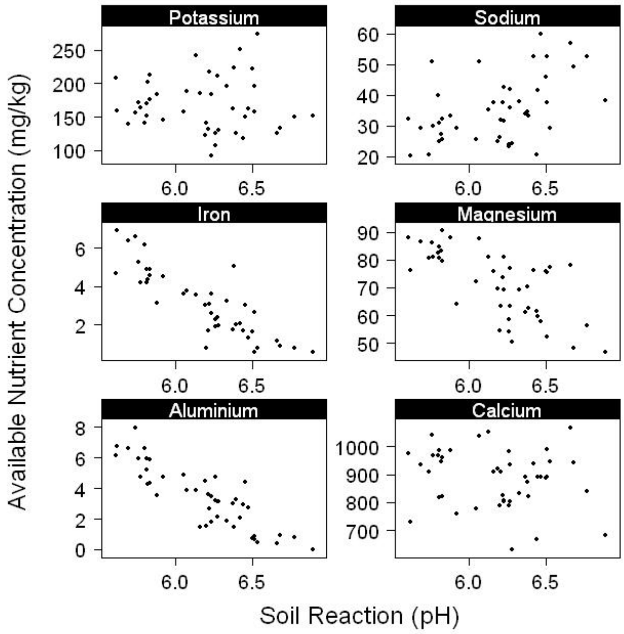


Figure 5.1. The effect of soil pH on soil nutrient concentrations.

Despite significant treatment effects on pH and the concentration of some soil nutrients (Na, Mg, Fe, Al), the mean concentration of nutrients in the leaves of *Platanus orientalis* generally did not differ with the installation of pavements (Table 4). Only manganese concentration in leaves differed as a result of pavement treatments, relative to controls (Table 5, contrast 1). Further inspection revealed that manganese was dependent on both pavement type and profile design, but not their interaction (Table 5, contrasts 2, 3, 4). Though leaf Mn concentration decreased in plots covered in porous rather than impervious pavements, the values for trees in IP and PP plots were similar to control plots. Large decreases in the concentration of Mn in leaves were observed in plots designed with a compacted subgrade and gravel base (IP+ and PP+). Subsequent linear regression corroborated and explained these results, showing that of all measured nutrients, only manganese leaf tissue concentration was dependent on soil pH, for the range of pH values in this experiment (Table 6). Over the range of pH values studied leaf manganese concentration decreased linearly with increasing pH.

Table 5.4. The effect of pavement type and profile design on leaf nutrient concentration. Values shown represent means (1 standard error).

	Leaf Nutrient Concentration (mg kg^{-1})													
Treatment	**Al**	**Cd**	**Ca**	**Cr**	**Cu**	**Fe**	**Mg**	**Mn**	**Ni**	**P**	**K**	**Na**	**S**	**Zn**
Control	34.17 (2.99)	0.09 (0.02)	9975.33 (526.49)	0.27 (0.01)	4.36 (0.26)	62.09 (4.02)	1366.02 (52.60)	28.9 (2.31)	0.37 (0.05)	1483.26 (35.88)	11586.96 (571.52)	213.84 (16.63)	1891.10 (105.37)	15.85 (0.61)
IP	31.17 (2.4)	0.07 (0.01)	9306.21 (370.02)	0.26 (0.01)	3.45 (0.52)	55.05 (2.50)	1269.79 (79.74)	32.15 (2.09)	0.30 (0.03)	1580.86 (63.09)	13111.03 (550.81)	182.18 (9.04)	2102.31 (81.46)	18.38 (1.49)
PP	34.65 (2.5)	0.06 (0.01)	8944.6 (350.35)	0.24 (0.01)	3.92 (0.34)	58.57 (3.05)	1209.48 (73.18)	25.63 (2.63)	0.38 (0.08)	1563.20 (51.20)	13589.02 (779.21)	183.23 (15.6)	1950.72 (102.09)	17.4 (1.66)
IP+	35.4 (2.79)	0.07 (0.02)	9414.96 (541.92)	0.23 (0.02)	3.42 (0.21)	55.07 (2.51)	1142.84 (34.45)	18.76 (2.3)	0.23 (0.05)	1498.48 (28.88)	12003.52 (581.16)	222.88 (12.59)	1868.85 (73.76)	15.77 (1.36)
PP+	36.63 (1.99)	0.07 (0.01)	10514.03 (581.53)	0.25 (0.01)	3.68 (0.33)	58.7 (2.58)	1380.54 (40.84)	15.58 (1.59)	0.37 (0.06)	1558.57 (58.77)	13445.02 (845.65)	203.49 (23.03)	2077.57 (80.49)	15.00 (1.17)

Table 5.5. p-values for single degree-of-freedom contrasts show differences in mean values for leaf nutrient concentration. * $p < 0.05$.

Contrasts	d.f.	p_{Al}	p_{Cd}	p_{Ca}	p_{Cr}	p_{Cu}	p_{Fe}	p_{Mg}	p_{Mn}	p_{Ni}	p_{P}	p_{K}	p_{Na}	p_{S}	p_{Zn}
1. Control vs. All other treatments	1	0.92	0.25	0.44	0.25	0.06	0.13	0.10	0.03*	0.34	0.24	0.06	0.40	0.30	0.62
2. Main effect (pavement profile design)	1	0.22	0.74	0.08	0.67	0.70	0.98	0.72	3.97E-06*	0.49	0.39	0.36	0.07	0.56	0.07
3. Main effect (pavement type)	1	0.35	0.79	0.44	0.84	0.31	0.23	0.16	0.03*	0.06	0.68	0.17	0.57	0.75	0.52
4.Interaction (pavement profile design x pavement type)	1	0.66	0.67	0.13	0.21	0.78	0.99	0.02*	0.45	0.68	0.45	0.48	0.53	0.05	0.94

Table 5.6. Regression coefficients of the linear functions of the form y = a + bx where y represents the concentration (mg kg-1) of each nutrient in leaf tissue, x represents the soil pH. * p < 0.05

Nutrient	Estimate	s.e.	Slope	s.e.	df	r2	p
Aluminium	16.52	22.18	2.87	3.58	42	0.02	0.43
Cadmium	0.30	0.13	-0.04	0.02	42	0.06	0.10
Calcium	9363.21	4400.62	41.56	709.37	42	8.17e-05	0.95
Chromium	0.44	0.14	-0.03	0.02	40	0.04	0.20
Copper	3.89	3.06	-0.02	0.50	41	3.82e-05	0.97
Iron	56.16	26.08	0.24	4.20	40	7.85e-05	0.96
Magnesium	1560.30	568.90	-45.90	91.90	43	5.77e-03	0.62
Manganese	105.59	23.77	-13.10	3.83	42	2.20e-01	1.40e-03*
Nickel	0.30	0.47	5.75e-03	0.08	34	1.70e-04	0.94
Phosphorus	1270.73	426.69	43.22	68.97	42	9.26e-03	0.53
Potassium	3541.80	5928.40	1492.90	957.60	43	5.35e-02	0.13
Sodium	144.97	145.71	8.94	23.50	41	3.52e-03	0.71
Sulphur	1400.73	810.32	94.81	130.62	41	1.27e-02	0.47
Zinc	21.82	12.08	-0.85	1.95	42	4.51e-03	0.66

Abbreviations: SE, standard error; df, degrees of freedom; r^2, coefficient of determination; p, probability of predicted value equalling or exceeding observed value.

5.4 Discussion

The treatment-related differences seen in soil nutrient concentrations were widespread, affecting four of the six measured nutrients. That being said, it is unlikely that the pavement treatments contributed directly to decreases in soil Al, Fe, and Mg, as well as to increases in soil Na. Rather, these changes are likely to be due to pavement's effect on underlying soil pH and the latter's effect on nutrient solubility.

The value of soil reaction, pH, is a measure of the concentration of hydrogen ions (H^+); low pH values are indicative of acidic soil and contain relatively more H^+ than alkaline soils which have high pH values. The results support pavement's effect on underlying soil pH. Relative to control plots, all pavement treatments increased the mean pH, with further distinctions 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 underneath roads (Park et al. 2010). The increase in soil pH from control (5.75) to paved plots (IP: 6, PP: 6.35, IP+: 6.26, PP+: 6.58) is attributed to the dissolution of cement paste, which was used as a binder in the concrete pavements. Portland cement contains calcium hydroxide ($Ca(OH)_2$) which, when reacting with CO_2 and H_2O in a process called carbonation, produces calcium carbonate ($CaCO_3$) and water (Grattan-Bellew 1996). The subsequent dissociation of calcium carbonate allows ionic calcium (Ca^{2+}) to replace two hydrogen ions (H^+) on negatively charged exchange sites in the soil. The carbonate ion (CO_3^{2-}) reacts with water to form bicarbonate (HCO_3^-), which subsequently reacts with H+ to form H_2O and CO_2 (Thomas and Hargrove 1984). Thus, the pH of the soil increases because the quantity of H^+ has decreased. This chemical process is identical to agricultural liming in which calcium carbonate is applied to soil to correct its pH; indeed, calcium hydroxide (slaked or hydrated lime) has been similarly used.

Previous studies have shown the link between concrete materials and leaching of calcium hydroxide (Haga et al. 2005). However, it was unknown whether porous concrete pavements would yield a different effect to impervious pavements. The results indicate that soil pH increased even more beneath porous, rather than impervious pavement (Table 2, contrast 3). This is likely to be due to increased leaching of Ca^{2+} into the underlying soil. As porous pavements contain a relatively greater proportion of cement than impervious pavements (Ferguson 2005), and are specifically designed to infiltrate water, it follows that more $Ca(OH)_2$ (in paste) is exposed to rainfall, resulting in greater Ca^{2+} inputs. Furthermore, the effect of pavement profile design yielded higher soil pH in plots with a compacted subgrade and gravel base than in those without. The aggregate provided by the supplier was not washed and would have been coated by small particles (< 75µm), known as microfines, which are comprised mainly of clays (Muñoz et al. 2010). It is probable that the increased pH in these plots is attributable to microfines.

The importance of pavement's effect on soil reaction was evidenced by the correlations of pH with soil nutrient concentrations. Four of the six measured soil nutrients were significantly correlated with pH, the exceptions being calcium and potassium. It has previously been shown that mineral solubility is highly dependent on pH in both organic (Lucas and Davis 1961) and mineral soils (Truog 1948). This was corroborated in this experiment as soil sodium was positively correlated with pH while Mg, Al, and Fe were negatively correlated. Evidently, any change to soil pH has an effect on nutrient solubility and thus, availability for uptake by plant roots. Not all minerals were affected by soil pH, namely potassium and calcium. However, potassium and, especially, calcium are highly available at a wide range of pH values and so it is unlikely they would vary much over the relatively narrow range of pH values (5.61-6.89) tested here.

By increasing pH and altering soil nutrient concentrations, it was expected that pavement treatments would affect plant nutrient uptake. But, with the exception of manganese, this did not occur. Plants are able to modify the pH of the rhizosphere by exuding exudates from their roots, thereby modifying the solubility of nutrients and making them available for uptake (Dakora and Phillips 2002). Because of this adaptation, plant species are able to take up nutrients from soils spanning a wide range of pH values; however, estimates for optimal plant function range from 5-7 (Epstein and Bloom 2005). This adaptability certainly helps explain how the concentration of nutrients in leaves were generally unaffected by treatments and the narrow range of pH values tested (5.61-6.89).

The one exception was manganese, whose concentration decreased in pavement treatments and especially in plots including a gravel base. At pH values above 5.5, Mn availability begins to decrease (Sarkar and Wynjones 1982), so it is likely that the elevated pH beneath pavement treatments decreased the availability of Mn. It is uncertain whether this reduction in Mn concentration had any impacts on the growth and function of *Platanus orientalis* as no formal tests were conducted to identify manganese deficiency, which is typically characterised by inter-veinal chlorosis and, in severe cases, malformed or necrotic leaves (Epstein and Bloom 2005). However, dieback and mortality of *Quercus alba* in a paved environment has previously been attributed to manganese deficiency (Messenger 1986). In this experiment, leaf manganese concentration decreased from 28.9mg kg^{-1} (in control plots) to 15.58mg kg^{-1} in PP+ plots, below levels recognised as adequate for *Acer saccharum* (23mg kg^{-1}) and *A. rubrum* (32mg kg^{-1}) (Smiley et al. 1985). Though nutrient deficiency is highly species specific, the significantly lower manganese concentrations in paved plots alludes to the possibility of a deficiency.

Though only leaf Mn concentration was affected by pavement treatments, it is important to recognise the implications of this result. All nutrients have solubility thresholds. 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 undoubtedly the potential to affect plant function and growth.

Increases in soil pH related to pavement should not be considered inherently positive or negative for plant growth and function. A plant's response to pavement-induced changes will depend only on the resulting pH. Two hypothetical examples can illustrate this. Plants growing in soils with an acidic reaction are prone to toxic concentrations of Al, Fe, and Mn in plant tissue (Sparks 2003); thus, an increase in pH resulting from a cementitious pavement would likely benefit plant growth and function. In contrast, a pavement-related increase in soil pH for a plant growing in a neutral soil would likely result in decreased availability of nutrients, most notably phosphorus, manganese, and boron which are largely insoluble in alkaline soil (Truog 1948).

5.5 Conclusion

The collection and analysis of soil reaction and nutrient availability data in this experiment provided only a snapshot of a dynamic process whereby soil chemistry is continuously affected by inputs of calcium carbonate from the overlying pavement. Nevertheless, all pavement treatments resulted in significantly greater pH, and changes in the availability of aluminium, iron, magnesium, and sodium. It is likely that the changes in nutrient availability are not directly related to pavement treatment, but rather that pavements modified the underlying soil pH which, in turn, affected nutrient solubility and thus, availability. The result was that, relative to control plots, soil underlying paved plots had increased soil Na, but decreased Al, Fe, and Mg. Porous pavements had an even greater effect than impervious pavements on soil nutrient concentrations, decreasing Al and Fe, while increasing K and Mg.

Despite significantly affecting soil reaction and nutrient concentrations, pavement treatments did not generally affect the concentrations of macro- or micro-nutrients in plant tissue. This points to the flexibility of plants to assimilate nutrients throughout a range of soil pH values. It is, however, possible that if pavements modified the soil pH to levels near the thresholds of nutrient solubility, then differences in leaf tissue nutrient concentration would be more obvious. Certainly the relative manganese deficiency in leaves of trees treated by pavements is indicative of this possibility. Due to the narrow range of pH values resulting from treatments in this experiment, it is unlikely that tree growth or function will be affected.

Chapter VI

Above-Ground Growth Response of *Platanus orientalis* to Porous Pavements

The contents of this chapter have been published as:

Morgenroth, J. and R. Visser. 2011. *Above-Ground Growth Response of Platanus orientalis to Porous Pavements*. Arboriculture and Urban Forestry 37(1): 1-5.

6.1 Introduction

The urban forest is a major infrastructure element, providing environmental, economic, and social benefits. Healthy, mature trees improve air and water quality (Heckel 2004; Xiao et al. 1998), moderate extreme temperatures (Long-Sheng et al. 1993), reduce energy consumption (McPherson 1994), increase real estate values (Anton 2005), provide wildlife habitat (Dunster 1998), and provide intangible benefits including aesthetic and recreational amenities. Street trees planted alongside roads and sidewalks comprise a major component of the urban forest. Street trees are subject to environmental stresses, both biotic and abiotic, which fluctuate and interact to affect plant function and growth. Furthermore, anthropogenic stresses compound the natural environmental stresses already imposed on trees. Buildings and pavements render ground surfaces impervious; stormwater management systems divert water away from soil and into designated reservoirs; soils are compacted to meet engineering standards, and trees are often planted in confined growing spaces. The additive effect of these, and other factors is that urban trees have comparably shorter life spans and reduced annual growth than their forest-based conspecifics (Quigley 2004).

One defining characteristic of the urban environment is impervious pavement. This infrastructure element is used for roads, parking lots, and sidewalks. It is pervasive, in some cases covering over 50% of land surfaces (Ferguson 2005). Trees surrounded by pavements have their growing environment altered; soil chemistry and physics are both modified by overlying pavements (Celestian and Martin 2004; Craul 1985; Jim 1997; Macdonald et al. 1993), as are a number of localised atmospheric factors, such as surface temperature and vapour pressure deficit (Kjelgren and Montague 1998). This has led to speculation that pavements cause decreased growth, premature decline, and death (Iakovoglou et al. 2001; Kjelgren and Clark 1994; Schröder 2008). The pavement profile for a load-bearing pavement will include, from bottom to top, compacted parent material (hereafter referred to as a subgrade), a gravel base, and typically, an impervious surface course. In contrast, the pavement profile design for non-load bearing pavements may include only a surface course installed over a compacted subgrade. Surface courses such as concrete or asphalt combine a well-graded mix of aggregates and a binder to maximise density and limit permeability. An alternative pavement type precludes the inclusion of fine aggregate and thus, results in a porous pavement. In contrast to impervious pavements, porous paving is characterised by a matrix of interconnected pores, which render it permeable to air and water. Porous pavements are generally perceived to promote tree growth and survival by enhancing moisture infiltration and increasing soil aeration (Ferguson 2005; Tennis et al. 2004). Theoretically, this is plausible, but these hypotheses have never been experimentally tested in a system including live trees. In this experiment, this gap in knowledge was addressed by testing the effects of porous and impervious pavement profile designs on tree height, diameter, and above-ground biomass.

6.2 Methods

6.2.1 Data Collection

Initial height and diameter were measured at the time of planting, in August 2007, prior to the first growing season; subsequent measurements occurred at the end of spring in the first growing season (December 2007), as well as the end of the first (March 2008) and second (March 2009) complete growing seasons. Tree height was measured as the distance between the soil surface and the tip of the apical bud on the leader of each tree, while the diameter was calculated as the average of two measurements taken perpendicular to one another 10cm above the soil surface. Mean initial tree height was 62cm and initial trunk diameter was 6.7mm. Neither initial height (p = 0.663), nor diameter (p = 0.961) differed significantly amongst treatments. Height and diameter growth were measured as the absolute growth occurring over the duration of the experiment. On 12 March 2009, all trees were harvested at ground level. This plant material comprised above-ground biomass and was dried in a kiln at 70°C to constant weight (Nicholson 1984).

6.2.2 Statistical Analysis

Stem height, diameter and above ground biomass were compared via one-way analysis of variance (ANOVA) using orthogonal, *a priori*, single degree-of-freedom contrasts to examine treatment effects, as well as, interactions of interest (Marini 2003). All significant differences are reported for $p < 0.05$. Analyses were performed using the R statistical package, version 2.8.1 (R Development Core Team 2008).

6.3 Results

6.3.1 Height Growth

While height growth was dependent upon treatment ($p = 0.022$), mean height growth of control trees was equivalent to all other treatments (Table 1, contrast 1), thus implying differences amongst the four pavement treatments. Alone, the pavement profile design had no effect on tree height, as the mean height growth of all PP and IP trees did not differ from all PP+ and IP+ trees (Table 1, contrast 2). Nevertheless, height was significantly affected by the interaction between pavement type and profile design (Table 1, contrast 4).

Table 6.1. Single degree-of-freedom contrasts comparing the effect of pavement type and profile design on total stem height and diameter growth, as well as above-ground biomass. * p < 0.05

Contrasts	**df**	p_{height}	$p_{diameter}$	$p_{biomass}$
1. Control vs. all other treatments	1	0.542	0.009*	0.007*
2. Main effect (pavement profile design)	1	0.083	0.001*	0.0003*
3. Main effect (pavement type)	1	0.033*	0.041*	0.004*
4. Interaction (pavement profile design x pavement type)	1	0.046*	0.015*	0.001*

Further investigation showed that without subgrade compaction or a gravel base, trees surrounded by porous paving grew approximately 205cm, while those surrounded by impervious paving grew only 160cm. However, in plots with a compacted subgrade and gravel base, a difference of less than 2cm existed between trees surrounded by porous and impervious pavement (Figure 1).

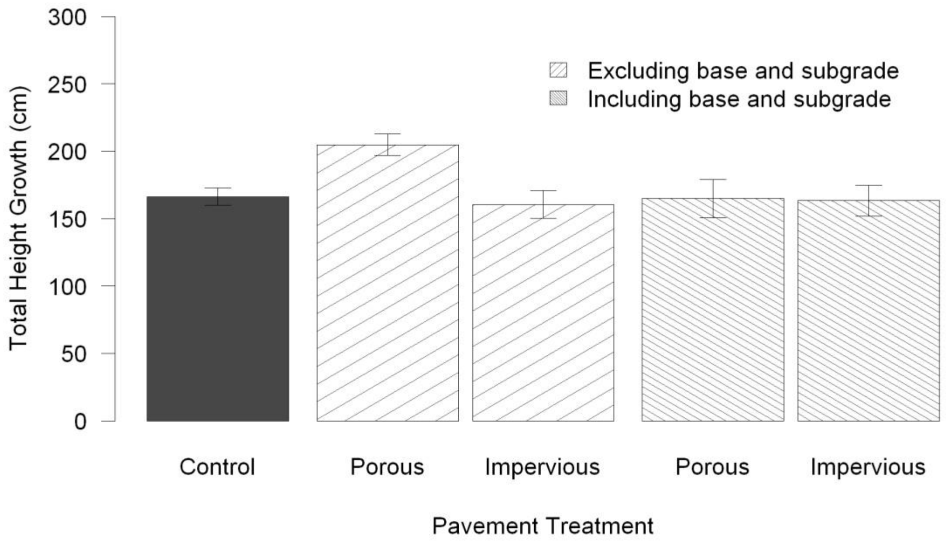


Figure 6.1. The effect of pavement type and profile design on mean height growth of *Platanus orientalis,* relative to control plots characterised by bare soil. Values represent total growth following two growing seasons. Error bars represent one standard error.

6.3.2 Diameter Growth

Stem diameter growth was also dependent on treatment (p < 0.001). Unlike height growth results, the mean diameter growth for all pavement treatments exceeded that for control trees (Table 1, contrast 1). While the effect of pavement profile design and pavement type were both significant, diameter growth depended on their interaction (Table 1, contrast 4). Diameter growth gains provided by porous pavement were limited to plots without a gravel base and subgrade compaction, as pavement type did not effect change in IP+ or PP+ plots (Figure 2).

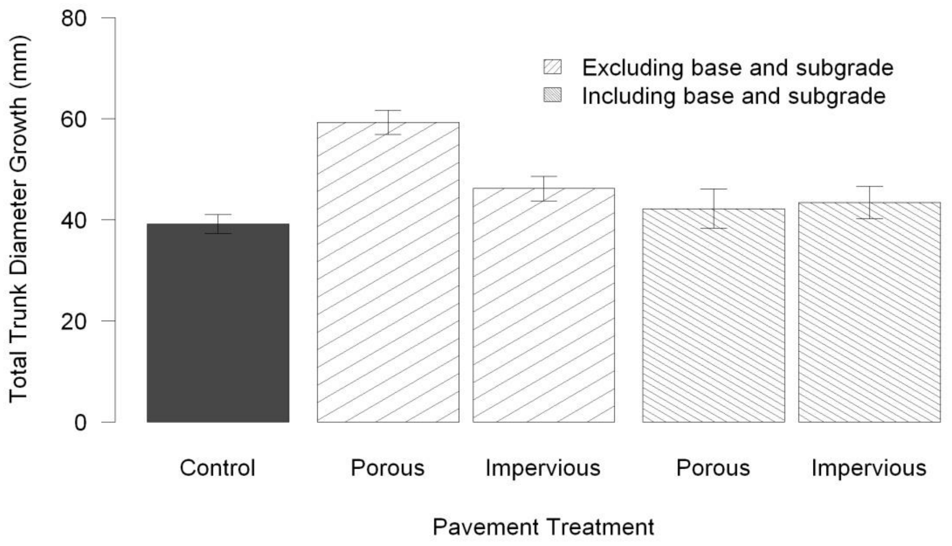


Figure 6.2. The effect of pavement type and profile design on mean trunk diameter growth of *Platanus orientalis*, relative to control plots characterised by bare soil. Values represent total growth following two growing seasons. Error bars represent one standard error.

6.3.4 Biomass

Above-ground biomass was dependent on treatment ($p < 0.001$) (Figure 3). Mean biomass for control trees was lower than the mean of treated trees (Table 1, contrast 1). While both pavement type and profile design main effects were significant, these factors exhibited a strong interaction (Table 1, contrast 4). Pavement type had no effect in plots with a compacted subgrade and gravel base, but trees in PP plots had significantly greater shoot biomass than trees in IP plots (Figure 3).

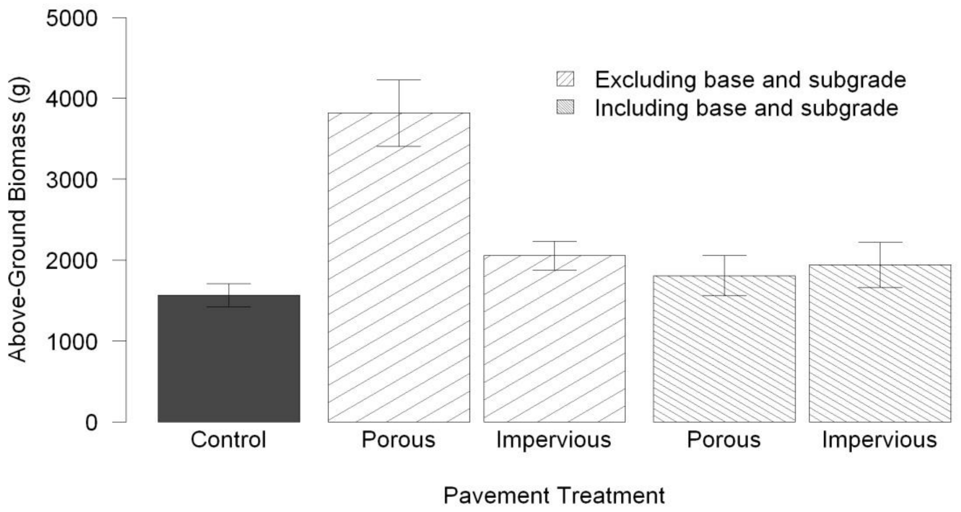


Figure 6.3. The effect of pavement type and profile design on mean shoot biomass of *Platanus orientalis*, relative to control plots characterised by bare soil. Values represent total growth following two growing seasons. Error bars represent one standard error.

6.4 Discussion

Within the context and limitations of this experiment, the results show that: 1) impervious pavements alone do not restrict or compromise tree growth, relative to control plots; and 2) relative to control plots and impervious pavements, porous pavements can improve tree growth, but only in the absence of a compacted subgrade and gravel base.

6.4.1 Effect of Pavement on Tree Growth

It is important to deconstruct pavements into their primary constituents, the pavement surface and the underlying structural layers including a subbase, subgrade, and base. Many of the problems faced by street trees are generally ascribed to pavements without distinguishing between the surface or underlying structural layers. In the 1970s, it was commonly believed pavement surfaces caused reductions in soil moisture by precluding infiltration (Roberts 1977), however, more recent research has indicated that street trees may suffer from too much, rather than too little water (Berrang et al. 1985) though it is unclear whether this is due to the surface or underlying soil compaction. Pavement surfaces have also been said to increase air

(Whitlow and Bassuk 1988) and soil (Celestian and Martin 2004; Graves 1994) temperatures above levels for optimal physiological function. Furthermore, soil compaction beneath pavements has been linked to poor plant performance (Smiley et al. 2006). As pavements are associated with soil moisture extremes, excessive soil and air temperature, and root-limiting soil compaction, it is easy to understand why decline in street trees is ascribed to pavements.

In spite of this, none of the pavement treatments in this experiment, negatively influenced tree growth relative to controls. In fact, tree height, diameter, and above-ground biomass were equivalent, or greater, in pavement treated trees relative to control trees (Table 1, contrast 1). This suggests trees do not necessarily suffer from reduced growth and vigour as a direct result of overlying pavements. It is not disputed that street trees in paved areas are often associated with reduced growth rates and low survival, as this is well established (Gartner et al. 2002). However, pavements themselves are not necessarily the direct cause of tree decline.

An alternative explanation is that street trees suffer from the compounding stresses often associated with pavements, such as restricted soil volume (Kopinga 1991), soil compaction (Philip and Azlin 2005), physical injuries to the stem and branches (Fostad and Pedersen 1997), air pollution (Su and Sun 2006), and soil pollution via salt or other chemicals (Marosz and Nowak 2008), and soil moisture extremes (Berrang et al. 1985).

These additional stresses were not measured in this experiment, except for soil compaction and soil moisture. The latter was measured as part of a larger experiment and it was found that soil moisture beneath pavements consistently exceeded those in bare soil (Morgenroth and Buchan 2009). Given adequate soil moisture and the absence of many stresses known to afflict street trees, it is understandable why pavements alone produced no negative impacts on tree growth in this experiment.

6.4.2 Effect of Porous Pavement on Tree Growth

It has been suggested that porous pavements may play a role in improving tree growth by ameliorating underlying soil conditions (Ferguson 2005). This experiment confirmed tree growth can be improved by porous, rather than impervious pavement, but only in the absence of a compacted subgrade and a gravel base, where trees surrounded by porous pavements were taller, had greater stem diameter and above-ground biomass than trees surrounded by impervious pavement (Table 1, contrast 4).

It would be easy to suggest that differences in growth must be associated with the permeability of the porous pavement, and thus, higher soil moisture. However, Morgenroth and Buchan (2009) found that soil moisture did not differ beneath porous and impervious pavements. Thus, other explanatory factors must be considered.

Knowing that increased growth occurred only in plots without a gravel base and compacted subgrade suggests that the benefits proffered by porous pavement are superseded by some factor associated with the profile design. One possibility is that soil compaction counteracted the effects of porous paving. Soil compaction is at odds with the requirements of trees, whereby highly compacted soils are known to negatively impact tree growth (Smith et al. 2001). In this experiment, soil penetration resistance in IP+ and PP+ plots was 2410kPa. In contrast, soil in IP and PP plots had mean penetration resistance of only 841kPa. In soils similar to those in this experiment, values between 2000kPa-3000kPa are sufficient to hinder root development (Sinnett et al. 2008). Thus, it is likely the compacted subgrade restricted root development, thereby negating the positive effects of porous pavement exhibited in plots without a compacted subgrade and gravel base.

The theory that soil compaction negates the benefits provided by porous pavements could have critical implications for future porous pavement installations. The vast majority of pavements are designed to bear heavy loads and thus, are underlain by highly compacted subgrade and base layers. Accordingly, the use of porous pavement for tree growth amelioration may be limited to areas such as sidewalks and low-use parking lots, unless steps are taken to minimise soil compaction. One way to minimise soil compaction is to use specially designed pavement profiles, whereby the pavements are engineered to withstand heavy loads, while avoiding soil compaction with the use of suspended pavements or accommodating compaction in soil design such as with CU-Soil^{TM}. While these alternatives have been proven to perform as intended (Buhler et al. 2007; Smiley et al. 2006), their prevalence is presently restricted.

6.5 Conclusion

In summary, the present experiment revealed differences in tree growth resulting from differing pavement types and profile designs. Results indicate that pavements, in the absence of other stresses, do not cause reduced tree growth, even if the profile design includes a compacted subgrade and gravel base. It was also concluded that porous pavement could improve the above-ground growth of trees relative to those grown in impervious pavement settings. However, this was dependent on the absence of a gravel base and subgrade compaction. This research provided a glimpse into porous pavement's effect on Platanus orientalis, a hardy species often planted as a street tree. More research is required to determine whether the results found here are applicable in varying climates, for different tree species, planted in different soil types, and surrounded by various pavement widths and configurations such as sidewalks, roads, or plazas. Given the increased installation of porous pavements in the urban environment, such future research would help explain the growth and survival of trees in the urban forest.

Chapter VII

Root Growth Response of *Platanus orientalis* to Porous Pavements

The contents of this chapter have been published as:

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7.1 Introduction

The root systems of different tree species have varying architecture and though some species have a deep tap root which penetrates vertically into the soil, root systems are typically shallow and wide-spreading. It is generally accepted that most roots grow in the upper 30cm of soil, and that they spread well beyond the crown (Gilman 1990). This architecture ensures stability and optimal access to water and minerals (Perry 1982). Unfortunately, in urban environments, shallow root growth conflicts with overlying pavements (Kopinga 1994; Nicoll and Armstrong 1998). As roots expand radially, they deform the soil above them, placing tensile stress on the upper surface of overlying pavements (Nicoll and Coutts 1997). While pavements are strong in compression they are weak in tension, so underlying root growth leads to eventual pavement failure. These conflicts negatively impact both pavements and trees, often necessitating the repair or replacement of both. It is important to recognise that not all pavement damage is due to underlying roots; engineering faults and underlying soil type can result in cracking too (Sydnor et al. 2000). Standard pavements are designed to be impermeable for structural purposes, but if they crack, they expose underlying soil to atmospheric conditions such as precipitation and relatively high oxygen concentration. D'Amato et al. (2002) found that significantly greater root growth was found beneath existing cracks, and suggested that increased soil aeration beneath the crack resulted in greater root growth. In what could be considered a positive feedback loop, root growth can cause pavement failure and pavement failure can promote root growth. Unlike structural pavements, some pavements are designed to be permeable to air and water; these are called porous pavements. While it had previously been suggested that porous pavements may be a solution to conflicts with roots (Barker

1988), high permeability may result in improved soil conditions for root growth and hence, increased incidence of conflict. To understand how different pavement types and profile designs affect underlying root growth, this experiment's objective was to contrast root growth in open grown trees with those surrounded by porous and impervious pavements.

7.2 Methods

7.2.1 Data Collection

Root growth and distribution was quantified by measuring total root biomass, as well as, categorising the abundance of roots by depth and diameter. Following concrete pavement removal in March 2009, a square trench was dug around each tree using an air-spade (Concept Engineering Group, Inc. Verona, PA) to expose roots (Plate 7.1). This technique allowed roots, ranging in size from fine through to coarse, to be exposed, counted, and measured (Nadezhdina and Čermák 2003). Trenches measured 20cm wide by 50cm deep, and the distance between the tree stem and the nearest point on the inside wall of each trench was 100cm. Root abundance in the trenches was categorised into three discrete root diameter classes (fine: < 2mm, medium: 2-5mm, and coarse: > 5mm), and six depth classes each comprising a 5cm deep soil layer.

Plate 7.1. Categorising root abundance of *Platanus orientalis* by diameter and depth. An air-spade exposed roots with minimal damage.

Following collection of abundance data, the air-spade was used to remove all remaining soil surrounding each tree, allowing excavation of whole root systems (Plate 7.2). Whole root systems were placed in a kiln and dried at 70°C to constant weight (Nicholson 1984).

Plate 7.2. Determining root biomass. Root systems exposed by an air-spade were kiln-dried and weighed.

The cumulative proportion of roots from the soil surface was calculated for all trees. Following Gale and Grigal (1987), an asymptotic non-linear model was used to describe vertical root distribution:

$$Y = 1 - \beta^{d} \qquad [1]$$

where Y is the cumulative proportion of roots counted between the soil surface and depth d in centimetres and β is the estimated parameter. β was used as a relative index of the vertical root distribution across treatments. High values of β are associated with relatively deep root systems, whereas low values indicate proportionally shallow root systems.

7.2.2 Statistical Analysis

One IP+ tree died between the first and second growing seasons and thus was excluded in all analyses. No roots were found below 30cm soil depth, so analyses were limited to the uppermost 30cm. Root abundance data were analysed using a generalised-linear model with a quasi-poisson distribution. Treatment differences were determined via analysis of deviance (Crawley 2007). Estimated β coefficients (Equation 1) and below-ground biomass were compared via one-way analysis-of-variance (ANOVA) using orthogonal, *a priori*, single degree-of-freedom contrasts to examine treatment effects, as well as, interactions of interest (Marini 2003). All significant differences are reported for $p < 0.05$. Analyses were performed using the R statistical package, version 2.8.1 (R Development Core Team 2008).

7.3 Results

7.3.1 Root Biomass

Below-ground biomass depended on treatment ($p = 0.002$). Mean root biomass of control plots did not differ from pavement treated trees, however there were differences related to pavement type and profile design, as well as their interaction (Table 1).

Table 7.1. p-values for single degree-of-freedom contrasts comparing the effect of pavement type and profile design on root biomass and β, the index used to measure vertical root distribution. * p < 0.05.

Contrasts	df	$p_{biomass}$	p_{β}
1. Control vs. all other treatments	1	0.062	< 0.001*
2. Main effect (pave nt profile design)	1	0.013*	0.002*
3. Main effect (pavement type)	1	0.047*	0.243
4. Interaction (pavement profile design x pavement type)	1	0.022*	0.976

In IP+ and PP+ plots, root biomass was unaffected by pavement type, but in the absence of a compacted subgrade and gravel base, root biomass beneath porous pavements significantly exceeded root biomass beneath impervious pavements (Figure 1).

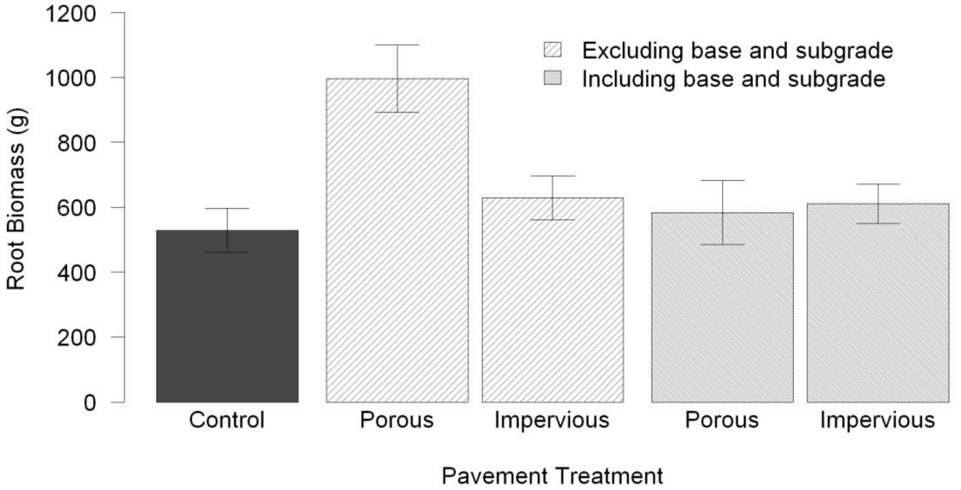

Figure 7.1. The effect of pavement type and profile design on mean root biomass of *Platanus orientalis*. Error bars represent one standard error.

7.3.2 Vertical Root Distribution

Root allocation was greatest at shallower depths with over 90% of roots, irrespective of treatment, growing in the uppermost 20cm of soil (Figure 2). The index used to measure vertical root distribution, β, ranged from 0.900 to 0.937 (Figure 2), where higher values signify relatively deeper root distribution (Gale and Grigal 1987). Control plots had comparatively higher β values than paved plots (Table 1, contrast 1), indicating that proportionally more roots grew deeper than in paved plots. Figure 2 illustrates this well; only c. 53% of roots from control trees grew in the uppermost 15cm of soil, whereas the percentage of roots growing in this same 15cm soil layer for pavement-treated trees was greater, ranging from c. 75%% to 84%.

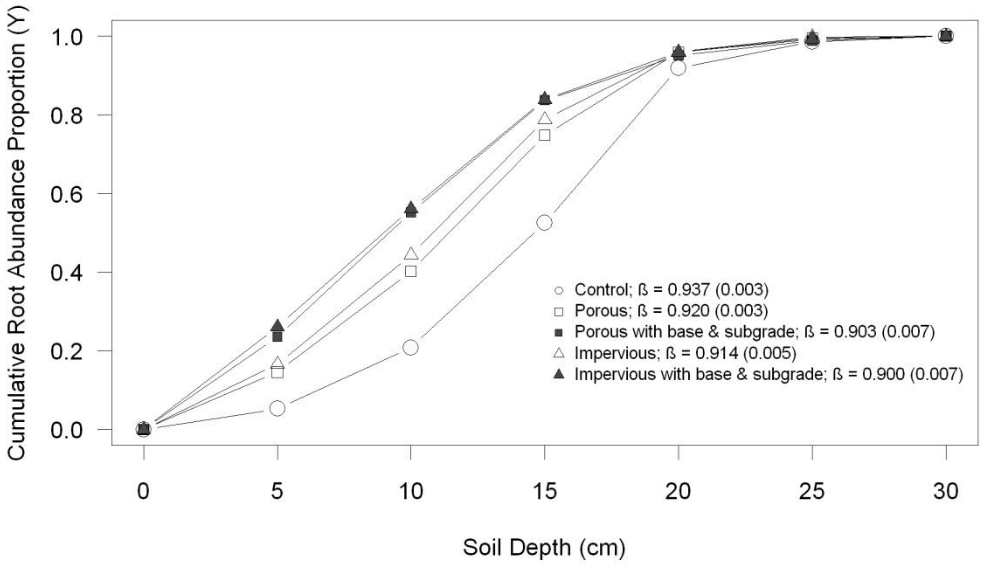

Figure 7.2. The effect of pavement type and profile design on cumulative root abundance (Y) with increasing soil depth (d). β values (1 s.e.) indicating vertical root distribution were derived from $Y = 1- \beta^{d}$.

Changes in pavement profile design also affected vertical root distribution (Table 1, contrast 2); roots grew relatively deeper under pavements without a compacted subgrade and gravel base, thereby resulting in a relatively higher β values for IP and PP plots (Figure 2). Pavement profile design differences were most prevalent in the uppermost 10cm, where c. 42% of roots grew in IP and PP plots, in contrast to c. 56% of roots from IP+ and PP+ plots (Figure 2). No pavement-type effect existed, implying that vertical root distribution beneath porous and impervious pavements was equivalent, regardless of pavement profile design.

7.3.3 Root Abundance

A comprehensive understanding of root dynamics was obtained by contrasting treatment effects on the abundance of roots of varying diameters at different soil depths. Some general trends, irrespective of root diameter class, were evident throughout the abundance data. First, within-treatment abundance generally increased in each successive 5cm soil increment throughout the uppermost 15-20cm (depending on treatment); below this, root abundance decreased abruptly (Figure 3).

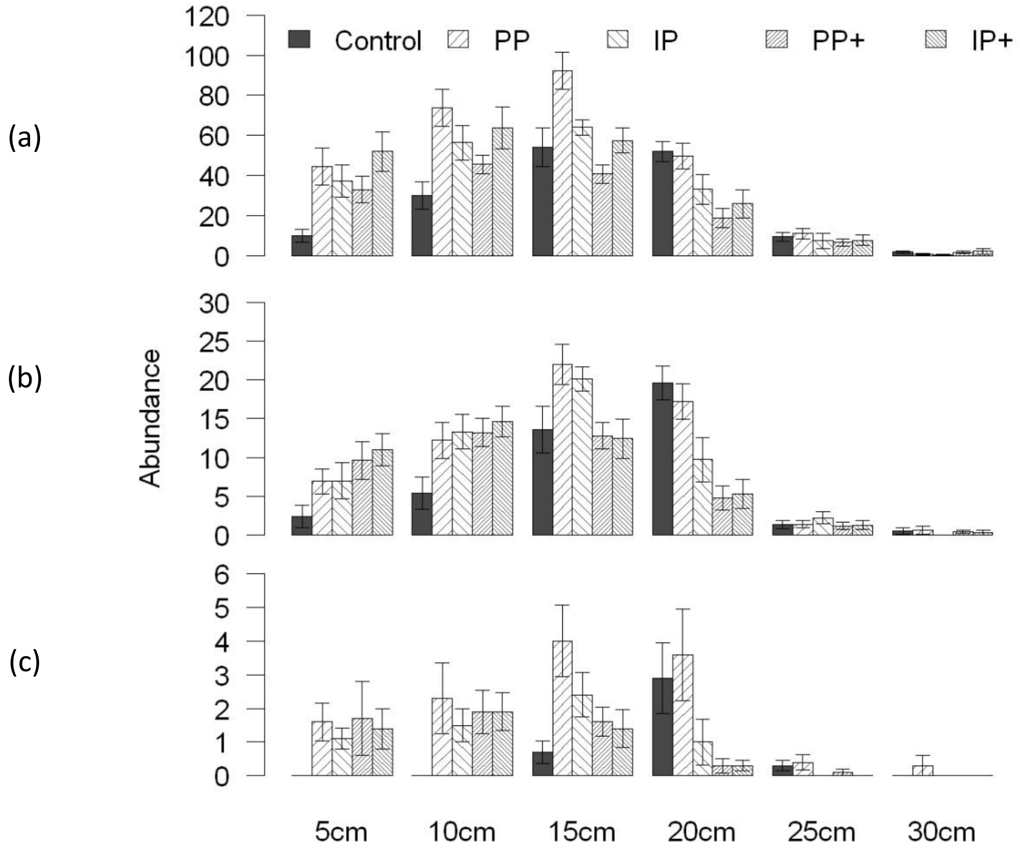

Figure 7.3. The effect of pavement type and profile design on mean abundance of roots by soil depth. Top: fine roots (< 2mm); Middle: medium roots (2-5mm); and Bottom: coarse roots (> 5mm). Note: the scale of the y-axis differs between plots.

Within each root diameter size class, treatment effects were present only in the top 20cm of soil. Abundance of roots from 20-30cm depth was statistically similar across all treatments (Table 2).

Table 7.2. p-values for single degree-of-freedom contrasts comparing the effect of pavement type and profile design on root abundance within root diameter and soil depth classes.

	Soil Depth (cm)																	
	0-5			**5-10**			**10-15**			**15-20**			**20-25**			**25-30**		
	Root Diameter (mm)																	
Contrast	**<2**	**2-5**	**>5**	**<2**	**2-5**	**>5**	**<2**	**2-5**	**>5**	**<2**	**2-5**	**>5**	**<2**	**2-5**	**>5**	**<2**	**2-5**	**>5**
1. Control vs. all other treatments	*0.001*	*0.020*	0.995	*0.003*	*0.004*	0.994	0.388	0.326	*0.046*	*0.005*	*<0.001*	*0.013*	0.621	0.895	0.994	0.325	0.995	0.999
2. Main effect (pavement profile design)	0.924	0.155	0.722	0.232	0.632	0.946	*<0.001*	*0.002*	*0.024*	*0.006*	*0.001*	*0.025*	0.475	0.367	1.0	0.084	0.995	0.999
3. Main effect (pavement type)	0.475	0.782	0.503	0.813	0.602	0.523	0.922	0.691	0.305	0.844	0.381	0.426	0.713	0.480	0.994	0.868	0.995	0.999
4. Interaction (pavement profile design x pavement type)	0.117	0.823	0.831	*0.046*	0.968	0.523	*0.005*	0.849	0.546	0.086	0.216	0.426	0.404	0.621	1.0	0.568	0.995	0.999

In the uppermost 20cm of soil, all pavement treatments altered root abundance and distribution relative to control plots (Table 2, contrast 1). Vertical root distribution followed a similar pattern in both fine and medium diameter roots. From the soil surface to 10cm depth, control plots had significantly fewer roots than paved treatments (Table 2, contrast 1). From 10-15cm depth, root abundance in control plots increased, whereas mean root abundance for paved treatments remained stable. As a consequence, no significant difference was found between controls and paved plots at this depth. Finally, between 15-20cm depth, a significant difference re-emerged; however, this time control plots had a greater abundance of roots than all paved plots.

A truncated version of this pattern existed for coarse roots. No difference existed between controls and paved plots in the uppermost 10cm, but then between 10-15cm depth, greater root abundance was exhibited beneath paved plots. The converse was true from 15-20cm, as root abundance was greater in control plots. Whereas root abundance beneath pavement treatments was greatest between 10-15cm deep, maximum root abundance in control plots did not typically occur until 20cm depth (Figure 3). This difference in root distribution was corroborated by β values, which suggested relatively shallow allocation of roots in paved plots and relatively deep allocation in control plots (Figure 2).

The effect of pavement profile design was seen in all three root diameter classes, but only in the layer 10-20cm beneath the soil surface (Table 2, contrast 2). In each root diameter class, the mean root abundance for IP and PP plots exceeded that for IP+ and PP+ plots. Thus, there were a greater number of fine, medium, and coarse roots in the 10-20cm soil depth under pavements without a compacted subgrade and gravel base.

Alone, pavement type never affected root abundance (Table 2, contrast 3), implying that mean root abundance was similar beneath porous and impervious pavements. Further inspection revealed an interaction between pavement type and profile design, which affected fine roots 5-15cm beneath the soil surface (Table 2, contrast 4). Without a compacted subgrade and gravel base, porous pavements yielded significantly greater fine root abundance than impervious pavements. Conversely, when pavement profiles were designed to include a compacted subgrade and gravel base, the abundance of fine roots was greater beneath impervious pavement (Figure 3a).

7.4 Discussion

The results support the hypothesis that root biomass differs beneath porous and impervious pavements, but only in the absence of a compacted subgrade and gravel base (Figure 1). Given that coarse roots contribute more to total root biomass than fine or medium fractions (Misra et al. 1998), it was believed that treatment differences would also arise in coarse root abundance. Within individual depth classes, this was rarely true, possibly due to low overall frequencies and high within-treatment variation (Figure 3). Nevertheless, a closer look was warranted, given the propensity for coarse roots to contribute to conflicts with pavements (Nicoll and Armstrong 1998).

Further inspection revealed that coarse root abundance, like root biomass, increased beneath porous pavement, but only in plots without a compacted subgrade and gravel base. The mean number of coarse roots found beneath PP treatments was 12.2, compared with only 6 for IP treatments. Mean values for control (3.9), PP+ (5.6), and IP+ (5) treatments are all comparable to IP. Of particular interest, the data reveals that in the uppermost 10cm of soil in control plots, no coarse roots were present, while paved plots had mean abundances ranging from 2.6-3.9 coarse roots per plot depending on treatment.

This is noteworthy because coarse roots at shallow depths have the potential to conflict with overlying pavements by deforming adjacent soil during radial growth (Nicoll and Armstrong 1998). It is likely that deeper root distribution for control plots is a response to diurnal temperature variation (Hillel 1998b) and fluctuating moisture (Morgenroth and Buchan 2009) which readily occur at shallow depths. In contrast, coarse roots did grow in shallow soil beneath pavements, where temperature and soil moisture were presumably more stable. Though high within-treatment variation compromised the statistical significance of the analysis, it is reasonable to suggest that coarse root abundance and biomass indicate the potential for pavements and, more specifically, porous pavements without a compacted subgrade and gravel base to result in larger root systems with the propensity for conflict with overlying pavements.

With greater than 90% of roots in the uppermost 20cm of soil (Figure 2), the root systems studied in this experiment were consistent with other root systems (Gilman 1990). It was in this 20cm soil layer that all treatment-related differences in root abundance existed. Results showed that root abundance was greatest in control plots at 20cm, whereas maximum values were reached in paved plots between 10-15cm. This difference is likely, indirectly or directly, in response to available soil moisture. As part of a larger experiment, Morgenroth and Buchan monitored soil moisture for all treatments in this experiment; they showed that, in control plots, soil moisture increased with depth (2009). Root branching and growth are known to increase under optimal soil moisture conditions (Ruark et al. 1983), presumably to take full advantage of the water resource, but also because soil strength is reduced at greater soil moisture, precluding physical obstructions to root growth. Thus, it is likely that the uppermost soil layer in control plots, which was highly prone to moisture fluctuations, and likely to temperature variation (Hillel 1998b), dissuaded root growth, while the deeper layers with more stable soil moisture and temperature promoted root growth.

In contrast to control plots, vertical root distribution beneath pavements was concentrated higher in the soil profile. Much as it did in control plots, high soil moisture may have promoted root growth in paved plots, beginning at shallower levels. This is because in paved plots, there was no dry zone, instead high soil moisture was found directly beneath pavements and extended deep into the soil profile (Morgenroth and Buchan 2009). Another explanation for shallow root growth beneath pavements also pertains to soil moisture, but in an indirect manner. The high soil moisture beneath pavements may have acted as a barrier to oxygen diffusion, leading to the relatively anaerobic conditions found deeper in the soil profile (Morgenroth and Buchan 2009). Since one response of roots to anaerobic soils is to remain near the soil surface (Dittert et al. 2006), it is possible that shallow root growth in this experiment was in response to anaerobic conditions present in the deeper soil layers beneath paved surfaces. Tree species with different tolerances to soil anaerobiosis would certainly have differed in their response as has been seen in other studies (Day et al. 2000).

Root abundance and distribution were also affected by pavement profile design. Trees exhibited relatively shallow root growth in paved plots designed with a compacted subgrade and gravel base (Figure 2). Differences in root abundance were significant between 10-20cm, where abundance was greater in IP and PP plots (Table 2, contrast 2). To explain these differences, we must consider how pavement profile design affected soil physical conditions, in particular, soil compaction. The rooting environment for trees in IP+ and PP+ plots included a compacted subgrade with mean soil strength of 2411kPa. Since soil strengths of between 2000-3000kPa are known to limit root growth (Sinnett et al. 2008), the compacted subgrade in IP+ and PP+ plots may account for lower observed mean root abundance. Another effect of compaction is reducing soil aeration; this is because macropores are lost in favour of micropores, which are preferentially filled by water rather than air. As previously explained, low soil aeration can cause shallow root growth, which may explain the relatively lower β values, and hence shallower root distribution, for IP+ and PP+ plots.

From the perspective of tree growth, pavement profile designs without a compacted subgrade and gravel base are preferable as these resulted in greater root abundance from 10- 20cm soil depth. Porous pavements were even more advantageous than impervious pavements given this profile design as they resulted in greater root biomass, as well as, enhanced above-ground growth (Morgenroth and Visser 2011). From the perspective of minimising conflicts between roots and pavements, the effect of porous and impervious pavements were similar; however, pavement profile designs which include a gravel base are preferable to those without. This is because, in this experiment, the inclusion of a compacted subgrade and gravel base resulted in fewer roots and, while those roots were significantly shallower within the soil profile, the gravel base ensured that they were never nearer 20cm from the underside of the pavement.

7.5 Conclusion

It is well accepted that though root architecture is under genetic control, the soil environment in which trees grow can influence root growth and distribution (Pritchett 1979). In this experiment, the soil environment was overlaid by pavement treatments. Previous research has shown that pavements can significantly impact a soil's physical characteristics such as soil moisture and aeration (Morgenroth and Buchan 2009), and temperature (Graves 1994; Wagar and Franklin 1994). These impacts offer a plausible explanation to the measured treatment effects including: greater root abundance and shallow root distribution in paved relative to unpaved plots; decreased root abundance below IP+ and PP+ plots relative to IP and PP plots; and greater root biomass beneath porous pavements relative to impervious pavements in the absence of a compacted subgrade and gravel base. Future studies should test the effect of these treatments on different tree species grown in various soil types and climates to validate and generalise these results.

Chapter VIII

Summary of Findings

8.1 Introduction

In addition to providing a comprehensive review of the pertinent literature, the aim of this thesis was to determine the effects of porous pavements, across two different profile designs, on the growth of street trees. By investigating growth as a function of pavement type and profile design, differences could be identified, but not explained. It was, therefore, of interest to explore the effects of pavement treatments on the edaphic factors known to affect tree growth, namely soil moisture, aeration, pH, and nutrient availability. By collecting and analysing this soil data, it was believed that this research might also explain the processes behind the pavement-related tree growth differences.

8.2 Soil and Tree Responses to Pavement Treatment

8.2.1 Soil Chemistry

Soil chemistry was invariably altered when covered by a pavement. Pavements alkalinised underlying soil, raising the pH from a moderately acidic reaction in control plots to relatively neutral in paved plots (Table 5.1). Such differences can alter mineral solubility (Truog 1948). and lead to deficiency or toxicity of some minerals (Larcher 2003). In this experiment, this was manifest by lower soil sodium concentration in control plots, but higher concentrations of the potentially phytotoxic metals magnesium, aluminium, and iron (Table 5.2). Meanwhile, paved plots had greater concentration of sodium. In spite of these differences, leaf nutrient concentration did not generally differ between control and paved plots (Table 5.5). This is probably because many plants are adapted to assimilate nutrients from a wide range of soil pH values (Epstein and Bloom 2005), exceeding the range of values resulting from pavement treatment.

8.2.2 Soil Moisture

Another effect of pavement was relatively higher underlying soil moisture during the great majority of the measurement period (Figure 4.1). Though counter-intuitive, this was not entirely unexpected as evidenced by observational (Whitlow et al. 1992) and empirical (Wagar and Franklin 1994) results. Beneath pavement, dips in θ_{soil} to values nearing the permanent wilting point were rare. The lowest θ_{soil} value measured beneath any pavement treatment was 16.3% (beneath PP+ at 20 cm in week 61). In comparison, control plots were characterised by soil moisture decreasing towards the permanent wilting point (at 5cm depth) for weeks at a time (Figure 4.2). The potential impact of this result on tree growth cannot be overstated, as photosynthesis and cell growth are intrinsically linked to adequate water availability (Mullet and Whitsitt 1996).

8.2.3 Soil Aeration

Given the inversely-proportional relationship between water and air occupying soil pore space, high soil moisture measured beneath paved plots likely contributed to significantly lower aeration (Table 4.1). However, the question of whether or not aeration beneath pavements is adequate for root respiration is inconclusive. Results showed that rods installed in paved plots were covered by a variegated combination of bright orange and dark corrosion. While the relative amount of bright orange or dark corrosion varied amongst pavement treatments, none exhibited a bright orange corrosion pattern over the whole rod, as found in control plots. The variegated pattern seen on rods in paved plots represents oxygen concentrations between 2-5% (Owens et al. 2008), well below the critical threshold of 10% for root function (Glinski and Stepniewski 1985). This suggests that aeration of soil beneath paved treatments limits root function.

Conversely, Watson (2006) determined that fine root density decreased consistently only when rusting occurred on less than 25% of the rod. Put in terms of this experiment, anaerobic scores of 9 or greater may indicate sufficiently low soil aeration to compromise fine root density. This never occurred on control rods at any depth, nor during any time period. But, it did occur during at least one time period for all pavement treatments at all depths, though most occurrences were for rods buried in plots with a compacted subgrade and gravel base. So, it is certainly possible to assert that aeration did differ between control and paved plots, and it is plausible that soil aeration below pavements is inadequate for optimal plant function.

8.2.4 Tree Growth

Since all explanatory soil variables differed significantly between control and pavement treatments, it was expected that all tree growth measurements would reflect this and, they too, would differ amongst control and paved treatments. But, only stem diameter and above-ground biomass (Table 6.1) were greater in paved plots, whereas stem height growth and below-ground biomass (Tables 6.1 and 7.1 respectively) were equivalent across controls and pavement treatments.

One possible explanation for this is that differences in explanatory soil variables counteracted one another, ensuring that growth differences could not simply be described by a combination of the measured soil variables. After all, pavements increased pH from moderately acidic to neutral, rendering a greater proportion of macro and micro nutrients available for uptake by roots. Furthermore, consistently high soil moisture in paved plots would favour tree growth relative to control plots. In contrast, relatively low soil aeration beneath pavements may have negatively impacted pavement-treated trees relative to controls. So, it is possible that growth increases in paved plots, related to higher soil moisture and favourable soil reaction, were offset by lower aeration. This may explain why observed differences in soil variables between paved and control plots did not necessarily result in subsequent differences in tree growth, as exemplified by height growth and below-ground biomass.

Another possibility is that not all variation in tree growth could be explained by the measured soil characteristics. Rather, some other, unaccounted factor influenced tree growth when surrounded by pavement. Some possibilities include, but are not limited to, soil temperature, air temperature, and relative humidity. Though these were not measured in this experiment, others have previously described their response to various urban surfaces, including both porous and impervious pavements, and it is possible to draw inferences about their potential effect on tree growth.

In paved environments, soil (Graves 1994) and air (Montague and Kjelgren 2004) temperature are higher than surrounding bare soil or vegetated surfaces. This is true for impervious (Graves 1994; Montague and Kjelgren 2004) and porous pavements (Asaeda and Ca 2000), with both pavement types having similar effects. Depending on when elevated soil temperature occurs, different tree growth responses can be expected. Since bud break (Greer et al. 2006) and root growth (Domisch et al. 2001) are both dependent on soil temperature, it is possible that higher spring soil temperature beneath pavement treatments caused early onset of bud break and greater root extension. Meanwhile, control trees may have remained dormant due to lower spring soil temperatures. Conversely, during the summer months, high soil temperature can lead to decreased root growth. The maximum temperature range for root growth rarely exceeds 25-30°C and elevated soil temperature can suppress root growth (e.g. Graves 1994; Ruark et al. 1983). So, while soil temperature was not measured in this experiment, the work of others suggests that soil temperature beneath pavements will be higher than in bare soil and may have influenced tree growth.

Pavement's effect on air temperature cannot be considered in isolation. Air temperature and relative humidity are intrinsically linked; higher air temperature in paved environments leads to lower relative humidity. With respect to tree growth, this creates a high vapour pressure deficit (VPD) between the leaf and the atmosphere. Depending on trees' physiological response, high VPD may have affected pavement-treated trees in this experiment. One response is to narrow the stomatal opening, reducing transpiration and water loss (Kjelgren and Clark 1993; Montague et al. 2000; Turner et al. 1984). Though narrowing stomatal aperture limits water loss, it also limits gas exchange, thereby reducing photosynthesis and growth.

Another response to low relative humidity and a high vapour pressure deficit is for stomata to remain open, which maintains transpiration and water loss, but also allows continued gas exchange and photosynthesis. If soil moisture uptake can meet transpirational demand, stomata will remain open, otherwise evaporative demand can exceed supply and water stress occurs (Kjelgren and Clark 1994; Potts and Herrington 1982). Clearly, the response can depend on soil moisture, but it is also species specific. *Platanus orientalis* leaves are believed to be well adapted to high temperature; normal photosynthetic rates can be maintained at 38°C due to isoprene emission by the leaves (Velikova et al. 2006). Certainly, air temperature over pavement would have been higher than over bare soil, so physiologically-limiting temperatures exceeding 38°C were more probable in paved plots. However, because of the small size of individual pavement plots ($2.3m^2$), and air mixing resulting from wind currents, it is unlikely that air temperature would have impacted tree growth differentially across treatments in this experiment.

A final possible explanation for the inconsistent differences in tree growth between control plots and paved plots relates to the variation amongst the four pavement treatments. High variation beneath pavement treatments, especially with respect to soil moisture and aeration may have precluded a consistent tree growth response, such that above-ground biomass and stem diameter differed between control and paved plots, but below-ground biomass and stem height did not.

Though tree growth responses were inconsistent, one certainty is that pavement treatments never reduced tree growth relative to control plots. This is an interesting result given that it is commonly speculated that pavements hinder tree growth and survival (Iakovoglou et al. 2001; Kjelgren and Clark 1994; Petersen and Eckstein 1988; Quigley 2004). Because pavement pads measured 2.3m^2, it could be suggested that pavement treatments were not sufficiently expansive to negatively affect tree growth. However, this is unlikely, as the pavement treatments were sufficiently expansive to significantly affect all measured soil characteristics, which in turn could have altered tree growth.

Because pavement treatments never reduced tree growth relative to control plots, it is suggested that trees do not necessarily suffer from reduced growth and vigour as a direct result of overlying pavements, but rather some combination of other factors prevalent in urban environments, but not in this experiment. This may include restricted soil volume (Buhler et al. 2007; Kopinga 1991; Lindsey and Bassuk 1991), soil compaction (Philip and Azlin 2005), physical injuries to the stem and branches (Fostad and Pedersen 1997), air pollution (Su and Sun 2006), and soil pollution via salt or other chemicals (Cekstere et al. 2008; Marosz and Nowak 2008). In the absence of these stresses, the effect of pavements alone produced no negative impacts on tree growth.

8.3 Soil and Tree Responses Amongst Pavement Treatments

8.3.1 Soil Chemistry

Though monitoring differences between control and paved plots was of interest, contrasting the response of soil and tree growth variables to the main effects of pavement type and profile design, as well as their interaction was the primary goal of this experiment. Differences in measured soil chemistry characteristics did result from both pavement type and profile design, but never their interaction. This means that soil pH and nutrient concentrations differed as a result of treatment with porous, rather than impervious pavement, irrespective of pavement design. Similarly soil pH and nutrient concentrations differed as a result of the inclusion of a compacted subgrade and gravel base, irrespective of pavement type.

Interestingly, greater pH occurred beneath porous pavements. Again, it is believed that due to the effect of pH on mineral solubility (Truog 1948), porous pavements indirectly lead to greater potassium (K) and sodium (Na) beneath porous pavements. Conversely, lower pH beneath impervious pavements lead to relatively greater concentration of soil aluminium (Al) and iron (Fe). With respect to the profile design treatment, pavements incorporating a compacted subgrade and gravel base yielded greater underlying soil pH than pavements without these structural elements; soil beneath these treatments also exhibited significantly lower concentrations of calcium (Ca), magnesium (Mg), Fe, and K. Despite differences in soil pH and nutrient concentrations amongst pavement treatments, differences in leaf nutrient concentrations did not generally result. So, it is unlikely that either treatment affected tree growth.

8.3.2 Soil Moisture

Like the response of soil chemistry characteristics, soil moisture was affected by both pavement type and profile design, but never their interaction. Probably due to the gravel base, which can prevent capillary rise (Christopher and McGuffey 1997), soil moisture in plots designed with a compacted subgrade and gravel base was consistently lower than in analogous plots without these structural elements. In these latter plots, distillation ensured greater soil moisture. Though the data show that the effect of pavement type on soil moisture was limited to short periods, it is believed that the timing of these differences may be crucial to plant growth during periods of drought. This is because porous pavement allowed relatively rapid recharge of soil moisture following rainfall events. This was exhibited following long periods without precipitation and hence, limited the duration of drought. As such, porous pavements may reduce periods of limited photosynthesis associated with drought stress (Mullet and Whitsitt 1996).

8.3.3 Soil Aeration

Differences in soil aeration amongst pavement treatments depended on season and soil depth. Generally, profile designs including a compacted subgrade and gravel base decreased soil aeration. This occurred during spring, summer, or both seasons, at all soil depths. The effect of pavement type was less pronounced, occurring only in the summer months. During this relatively dry period, soil aeration was greater beneath porous pavements at shallow depths (0-24cm), but only in plots designed with a compacted subgrade and gravel base. In plots without these structural elements, porous pavements did not impact aeration any differently than impervious pavements (Table 4.1, contrast 4). Others have shown that low soil aeration can limit root growth (Watson 2006), so it would be expected that treatments allowing for greater aeration would benefit tree growth.

In summary, the results showed significant main effects, whereby porous pavements increased soil pH, K and Na concentration, as well as soil moisture (for some time periods), while decreasing the concentration of potentially phytotoxic Al and Fe. Meanwhile, a significant pavement design main effect showed that pavements incorporating a compacted subgrade and gravel base decreased the availability of Ca, Fe, Mg, and K, and consistently decreased soil moisture and aeration. Evidently, the response of soil factors to pavement treatments was generally independent of the interaction between pavement type and profile design. The exception was soil aeration during the summer months, which was greater beneath porous pavements, but only in the absence of a compacted subgrade and gravel base.

8.3.4 Tree Growth

It had been hoped that by measuring soil characteristics known to affect plant growth, this study would determine whether tree growth differed when surrounded by porous or impervious pavement, and also provide an explanation for why. Soil chemistry, moisture, and aeration generally responded only to the main pavement treatment effects, not their interaction. If variation in tree growth depended only on measured soil factors, it could be inferred that growth would also respond only to the main treatment effects. Simply put, growth would increase as a result of porous paving, irrespective of pavement profile design. This, however, was not the case. The results show that height, diameter, above- and below-ground biomass of *Platanus orientalis* did increase significantly when treated by porous, rather than impervious pavement; but, this increase occurred only in the absence of a structural profile design, including a compacted subgrade and gravel base. So, the effect of treatments on measured soil characteristics alone, cannot fully explain the response of tree growth to treatments.

This disparity between the response of soil characteristics and tree growth to pavement treatments suggests one of three things. First, that any improvement in soil moisture, aeration, or soil chemistry resulting from treatment with porous pavement was negated by treatment with a compacted subgrade and gravel base. If this were true, one or more of these soil factors would have been influenced by the interaction of the pavement type and design, such that the measured soil characteristic would improve with respect to tree growth, but only in the absence of a compacted subgrade and gravel base. As this was not the case, this theory must be dismissed.

A second explanation acknowledges that soil moisture, aeration, and pH were improved by porous, rather than impervious pavement, irrespective of profile design. Why then, were increases in tree growth due to porous pavement limited to plots without a compacted subgrade and gravel base? Clearly, some factor associated with pavement profile design supersedes the effect of porous pavement. To be clear, it is suggested that the compacted subgrade and gravel base restricted the growth-related benefits associated with improved soil moisture, aeration, or pH beneath porous, rather than impervious pavements.

While the gravel layer may have some effect, the most likely limiting proponent of the profile design treatment is elevated soil strength, which has been shown to negatively affect tree growth under a variety of conditions (see review in Kozlowski 1999). Effects of elevated soil strength include reduced root length (Misra and Gibbons 1996), which limits the volume of soil which can be explored for minerals and water. This, in turn, can restrict above-ground development. If root development were negatively impacted by soil strength in this experiment, it would be reasonable to expect a significant main effect associated with the profile design treatment. Interestingly, below-ground biomass, as well as abundance of all roots between 10-20cm soil depth was significantly lower when the profile design included a compacted subgrade and gravel base. This result, together with evidence from other studies showing the impact of soil strength on root development, strongly suggests that soil strength in plots with a compacted subgrade and gravel base precluded increased tree growth, which might have otherwise resulted from the soil conditions below porous, rather than impervious pavement.

8.4 Implications

The results of this experiment conditionally support the unfounded assertions made by others such as Tennis et al. (2004) who suggested that porous paving is “ideal for protecting trees in a paved environment”, or Ferguson (2005) who stated that porous pavement can “increase the longevity of trees by improving moisture and oxygen relations”. Of course, any growth improvements in this experiment were contingent upon exclusion of a structural pavement profile design, including a compacted subgrade and gravel base. The implications discussed hereafter assume that this condition is met, and a conducive soil environment is present below the pavement surface course.

Improved tree growth is generally considered desirable, as many of the benefits associated with urban forests are dependent on tree size, in particular, leaf area (Peper and McPherson 2003). These benefits include improved air and water quality (Heckel 2004; Xiao et al. 1998), moderation of extreme temperatures (Long-Sheng et al. 1993), reduced energy consumption (McPherson 1994), increased real-estate values (Anton 2005), provision of wildlife habitat (Dunster 1998), and numerous intangible benefits including aesthetic and recreational amenities. Improved growth would be most beneficial in areas characterised by low canopy cover where these environmental, social, and economic benefits are limited. The role for porous pavements is especially important in densely paved urban centres. In these areas, porous pavement could promote greater growth and hence increase all benefits associated with canopy cover. Though densely paved urban centres stand to benefit most, pavement cover is ubiquitous in urban areas (Ferguson 2005) and so, the urban forest as a whole could benefit from the installation of porous rather than impervious pavements.

It should be considered that greater tree growth may not always be desirable, particularly in areas where above- or below-ground space is limited. This is because faster growth rates associated with porous pavement cover will result in trees outgrowing their designed spaces more quickly. In these situations, the installation of porous pavement must be reconsidered. Below the soil surface, large, fast-growing roots displace more soil as they expand radially, applying greater forces to the overlying pavement, which can result in cracking and uplifting. Knowing that porous pavements result in faster growing root systems, it is possible that they contribute to greater incidence of conflict between tree roots and pavement, relative to impervious analogues. Given the extensive conflicts which already occur between roots and pavements (McPherson 2000), it would be undesirable to exacerbate this situation.

The potential for porous pavement to be used for tree growth improvement seems presently limited, because pavements profile designs including a compacted subgrade and gravel base negate the benefits provided by porous pavements. In order to perform as intended, they would have to be installed over uncompacted soil, which is uncommon in urban areas as it opposes engineering requirements. Furthermore, in situations where less compaction is necessary in the pavement profile design, such as in low-use parking lots or sidewalks, porous pavements cannot be recommended because the resulting increased root growth may contribute to pavement damage, unless roots are spatially separated from overlying porous pavements. Spatial separation implies that the pavement surface course does not rest, or rely, on the soil for structural support. So, the use of porous pavements seems ideally suited for vaulted pavement designs. Here, porous pavements could successfully improve root growth in the uncompacted soil below without the concern of contributing to conflict.

8.4 Conclusion

In summary, by contrasting the growth of *Platanus orientalis* in a factorial arrangement of pavement types (porous/impervious) and profile designs (with/without compacted subgrade and gravel base) with control trees, this thesis determined that pavements modify underlying soil pH, nutrient concentrations, moisture, and aeration. These changes resulted in increased stem diameter and above-ground biomass, but not stem height or below-ground biomass.

Interestingly, no growth measurements were reduced by pavement treatment. Furthermore, this thesis determined that tree growth can be increased by porous relative to impervious pavement. Increased growth, however, was contingent on the absence of a compacted subgrade and gravel base. From this, it can be inferred that while pavement porosity is important to tree growth, its benefits can be negated by other factors, most probably, soil compaction.

Though it was important to have answered whether tree growth was affected by porous pavement, arguably the greatest contribution of this thesis is gaining an understanding into how porous pavements affected soil moisture, aeration, and soil chemistry. It is now understood that porous pavements improved tree growth in this experiment by allowing for rapid infiltration of rainwater, which reduced the duration that trees experienced drought stress. In addition, they allowed for greater underlying soil aeration, and finally, neutralised the moderately acidic soil. Without this basic understanding, it would be easy to misinterpret the unconditional assertions made by other authors that porous pavements improve growth (Ferguson 2005; Tennis et al. 2004).

Clearly, surrounding trees with porous pavements with the intention of increasing tree growth must be assessed on a case-by-case basis, taking into account characteristics of the proposed planting site, including soil type and pH, as well as, the tree species to be planted. This thesis has successfully determined the impacts of porous pavements on tree growth and soil characteristics, and by doing so, will complement the existing literature on the effects of various surface types on the growth and physiology of urban trees.

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Appendices

Appendix A – Mean Soil Moisture Values and Statistical Contrasts

The first three tables (A1-A3) contain the weekly mean soil moisture values at 5 cm, 10 cm, and 20 cm depth. These are the same values presented in Figure 4.2. However, for clarity, Figure 4.2 excluded any indication of variance. The tables presented here include the standard error for each calculated mean. The subsequent four tables (A4-A7) present the results of statistical analyses. These show *t* and *p* values for four pre-planned contrasts:

1. Control v. 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 X pavement type.

Table A1. Weekly mean soil moisture at 5 cm depth for control and all pavement treatments. S.E.: 1 standard error.

	Treatment									
	Control		IP		PP		IP+		PP+	
Week	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.
1	28.31	2.14	44.53	4.41	45.00	3.08	26.08	0.93	28.87	1.90
2	23.75	2.14	44.48	4.34	44.36	3.02	26.39	1.10	27.55	1.82
3	18.69	2.11	43.99	4.28	43.36	3.07	26.54	1.12	26.86	1.99
4	15.26	1.95	43.72	4.24	41.85	3.31	26.74	1.21	26.28	2.25
5	15.22	2.33	41.97	3.77	40.74	3.36	27.13	1.25	26.32	2.56
6	16.57	2.48	41.00	3.80	39.81	2.99	27.21	1.24	26.66	2.74
7	17.31	2.42	39.03	4.45	39.13	2.85	27.48	1.20	27.00	2.69
8	16.84	2.52	37.98	4.24	37.79	2.62	27.59	1.16	26.90	2.85
9	22.37	2.62	37.49	4.04	38.07	1.97	28.16	1.11	27.95	2.17
10	26.99	2.72	36.80	3.79	38.54	1.53	29.43	0.90	29.15	1.42
11	21.45	2.76	39.92	3.43	38.12	1.91	28.26	0.59	26.84	1.66
12	27.46	2.52	39.25	3.32	37.81	1.34	27.99	0.75	28.65	1.78
13	23.31	2.64	39.06	3.40	36.76	1.50	27.94	0.88	27.08	1.82
14	20.78	2.50	39.31	3.36	35.38	1.58	28.38	0.98	26.16	1.78
15	19.54	2.39	38.59	2.99	34.55	1.73	29.24	2.13	25.79	1.67
16	20.35	2.30	37.67	2.68	34.48	1.66	29.53	2.41	25.97	1.64
17	25.59	2.28	35.75	2.12	34.51	1.45	28.75	2.43	26.84	1.50
18	25.22	2.46	35.40	1.82	34.57	1.34	29.56	2.55	26.33	1.43
19	26.90	2.32	33.96	1.52	34.55	1.20	28.83	2.57	26.69	1.38
25	28.02	0.99	32.06	1.40	36.37	2.27	28.67	2.78	28.02	1.27
26	28.69	1.01	31.70	1.56	36.58	2.03	28.62	2.62	29.26	1.11
27	26.84	1.03	32.45	1.59	35.95	2.15	29.26	2.69	27.78	1.29
28	27.90	0.99	31.73	1.65	35.91	1.66	28.69	2.65	29.12	1.14
29	30.60	1.13	32.16	1.78	36.72	1.42	29.92	2.46	30.64	1.08
30	30.48	1.13	32.02	1.77	36.50	1.44	30.25	2.44	30.44	1.12
31	29.39	1.14	32.70	1.89	36.33	1.81	29.99	2.58	29.50	1.23
32	30.80	1.14	33.33	1.87	37.40	1.84	30.39	2.67	29.92	1.25
33	32.41	1.05	33.33	1.88	37.91	1.66	31.71	2.71	31.18	1.11
34	35.00	1.55	34.55	1.96	38.52	1.67	35.62	3.13	34.54	1.16
35	34.25	1.41	33.78	1.88	36.63	0.80	35.09	2.47	34.29	0.84
36	32.20	1.30	33.87	1.98	35.76	0.93	32.60	2.11	32.13	0.90
37	35.07	1.27	36.28	2.22	36.83	0.79	35.54	1.96	33.72	0.86
38	33.51	1.34	35.58	2.35	36.29	0.86	35.12	1.64	33.17	0.78
39	32.83	1.28	35.79	2.65	36.03	0.87	34.40	1.62	32.75	0.77
40	30.20	1.18	36.09	2.76	35.64	0.94	32.43	1.52	30.31	1.03
41	28.68	1.17	36.38	3.18	35.63	0.96	31.75	1.48	29.42	1.17
42	28.23	1.30	36.37	3.52	35.78	0.91	31.10	1.57	29.16	1.15
43	25.84	1.57	36.74	3.53	35.98	1.00	30.87	1.64	28.49	1.26
44	21.67	1.74	36.40	3.11	35.97	1.03	30.56	1.71	27.79	1.35
45	17.57	1.63	35.76	3.04	35.29	0.98	30.36	1.73	27.16	1.35
46	23.53	1.84	35.74	2.81	36.30	0.73	30.32	1.75	28.59	1.26
47	19.91	1.68	35.68	2.90	35.60	0.82	30.24	1.72	27.85	1.28
48	18.00	1.60	35.00	2.52	35.49	0.78	29.85	1.77	27.56	1.28
49	15.07	1.30	35.86	2.64	35.09	1.06	30.01	2.02	26.83	1.38
50	14.17	1.41	36.07	3.35	34.35	1.20	29.44	2.08	26.04	1.49
51	14.22	1.56	36.19	3.32	34.52	1.48	29.02	2.27	25.36	1.75
52	14.85	1.75	35.73	3.06	34.80	1.68	28.81	2.30	25.14	1.95
53	16.33	1.99	35.40	2.80	35.25	1.56	28.62	2.26	25.37	1.83
54	24.84	2.20	35.08	2.58	35.69	0.99	28.71	2.07	28.28	1.22
55	20.99	2.43	35.77	2.33	34.61	1.73	29.47	2.01	26.32	1.29
56	19.32	2.46	35.12	2.20	33.36	2.53	28.62	1.91	26.12	1.31
57	16.95	2.49	33.68	2.49	30.70	3.86	27.31	2.12	24.52	1.30
58	17.12	2.48	31.14	2.41	29.31	4.13	25.68	2.69	23.62	1.48
59	16.36	2.50	28.01	2.57	27.15	4.46	23.92	3.25	21.72	1.67
60	15.32	2.30	25.00	2.56	25.18	4.28	22.56	3.36	19.99	1.94
61	16.10	2.16	22.14	2.53	24.23	3.95	21.28	3.23	19.29	1.86
62	27.53	2.91	20.77	2.50	27.54	2.94	20.91	3.15	24.03	0.92
63	30.67	2.27	21.26	2.72	31.22	1.87	21.82	3.26	27.86	1.03
64	29.12	2.00	22.03	2.94	31.62	1.80	22.53	3.04	27.12	1.18
65	27.18	2.19	21.95	3.13	30.75	1.91	22.32	2.62	25.89	1.08
66	28.63	2.11	21.56	3.12	31.26	1.80	21.43	3.36	26.61	1.15

Table A2. Weekly mean soil moisture at 10cm depth for control and all pavement treatments. S.E.: 1 standard error.

	Treatment									
	Control		IP		PP		IP+		PP+	
Week	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.
1	29.31	1.02	45.48	4.81	43.14	4.51	25.20	3.33	28.01	1.20
2	28.73	0.91	45.38	4.73	42.15	4.52	25.47	3.47	26.91	1.11
3	24.90	1.81	45.05	4.67	41.52	4.43	25.27	3.61	26.14	1.06
4	21.26	2.24	44.68	4.60	40.62	4.47	24.82	3.75	25.34	1.06
5	21.23	2.20	44.17	4.49	39.67	4.57	24.73	3.95	24.97	1.17
6	21.45	2.14	43.06	4.44	38.13	4.62	24.57	3.98	25.00	1.36
7	22.34	2.11	42.49	4.33	36.96	4.67	24.51	4.05	25.25	1.47
8	22.07	2.11	41.52	4.27	35.40	4.54	24.49	4.25	24.78	1.65
9	25.44	1.49	40.79	4.15	35.31	4.02	25.43	4.10	26.60	1.47
10	29.21	1.19	40.20	3.95	36.92	2.93	27.18	3.63	28.57	0.74
11	25.59	1.87	40.80	3.82	35.67	3.32	25.06	3.65	26.20	0.78
12	28.37	1.30	39.65	3.76	35.86	2.59	24.79	3.27	27.29	0.79
13	26.71	1.51	39.32	3.71	34.38	2.89	24.73	3.55	26.05	0.82
14	25.73	1.64	38.82	3.65	32.52	3.22	24.16	3.82	24.88	0.78
15	25.14	1.63	38.30	3.63	31.61	3.36	23.90	4.05	24.18	0.85
16	24.93	1.68	37.30	3.71	31.63	3.19	23.52	3.97	23.98	0.94
17	25.64	1.52	35.70	3.53	32.11	2.48	23.41	3.47	24.70	0.89
18	26.32	1.55	34.98	3.07	31.37	2.68	23.43	3.30	24.49	0.84
19	26.66	1.48	32.82	2.18	32.39	2.26	23.03	2.83	24.76	0.87
25	29.81	1.34	30.25	1.32	33.13	2.57	23.87	2.12	26.33	0.88
26	31.14	0.95	29.88	1.26	33.37	2.19	24.13	2.02	27.64	0.80
27	29.78	1.23	30.35	1.26	32.97	2.30	24.25	2.24	26.53	0.85
28	30.29	0.81	29.92	1.19	33.00	1.87	24.07	2.05	27.47	0.78
29	31.68	0.30	30.20	1.17	33.92	1.37	25.73	2.35	29.25	0.62
30	31.79	0.37	30.17	1.15	34.19	1.11	26.13	2.55	29.34	0.66
31	31.04	0.38	30.56	1.11	34.18	1.46	25.62	2.40	28.53	0.75
32	31.69	0.31	31.13	1.02	34.92	1.80	25.80	2.44	28.68	0.71
33	33.69	0.45	31.31	0.98	35.37	1.61	27.25	2.57	30.10	0.59
34	36.51	0.87	32.35	1.01	35.90	1.65	32.96	3.22	33.86	0.50
35	36.09	0.74	31.91	0.93	34.40	0.63	32.61	2.35	33.81	0.27
36	33.83	0.50	31.45	0.95	33.77	0.57	30.54	2.56	31.73	0.46
37	36.30	0.29	33.37	1.28	35.10	1.22	32.51	1.74	33.15	0.39
38	35.03	0.51	32.62	0.89	34.76	0.84	32.29	1.90	32.77	0.44
39	34.61	0.48	32.52	0.93	34.68	0.84	31.87	2.13	32.42	0.40
40	32.18	0.40	32.54	1.10	34.44	0.70	28.80	2.56	29.87	0.69
41	31.02	0.40	32.56	1.19	34.52	0.69	27.68	2.60	28.91	0.74
42	30.40	0.39	32.40	1.25	34.57	0.76	27.07	2.70	28.48	0.76
43	28.85	0.56	32.67	1.33	34.71	0.81	26.56	2.80	27.80	0.79
44	26.09	1.11	32.91	1.39	34.98	0.89	26.03	2.92	27.28	0.81
45	22.39	1.64	32.83	1.44	34.66	0.99	25.15	2.81	26.60	0.77
46	25.58	0.92	32.79	1.47	35.18	1.05	24.92	2.60	27.39	0.78
47	24.16	1.05	32.72	1.53	34.76	1.07	24.44	2.63	26.45	0.82
48	22.95	1.15	32.50	1.57	34.51	1.13	23.90	2.21	26.11	0.79
49	20.78	1.15	33.31	1.62	34.98	1.50	23.77	2.41	25.38	0.80
50	19.89	1.38	32.85	1.56	34.62	1.73	23.78	2.88	24.51	0.89
51	19.96	1.40	32.83	1.55	34.92	2.14	23.13	2.86	23.80	1.11
52	20.13	1.31	32.00	1.66	34.85	2.46	23.08	3.30	23.37	1.39
53	20.65	1.16	31.12	1.75	35.04	2.61	22.71	3.33	23.54	1.36
54	27.48	0.94	30.39	1.80	35.37	1.70	23.11	2.55	26.56	0.88
55	26.06	1.44	30.77	1.87	34.98	1.68	23.02	2.87	24.95	0.83
56	24.82	1.37	28.35	1.62	34.08	2.00	22.28	3.08	24.15	0.80
57	23.75	1.39	26.73	1.66	32.49	2.56	21.33	3.38	22.45	1.16
58	23.39	1.42	25.68	1.86	31.32	3.02	20.47	3.55	21.48	1.51
59	21.89	0.90	24.14	2.04	28.95	3.16	19.72	3.55	20.32	1.71
60	19.55	0.67	22.49	2.16	26.44	3.29	18.84	3.55	19.10	1.69
61	18.74	0.48	20.84	2.24	24.70	3.01	17.84	3.27	18.46	1.55
62	22.97	0.52	19.64	2.20	28.40	2.66	18.49	2.65	23.08	0.83
63	29.68	0.80	19.78	2.21	28.06	3.69	20.13	1.96	26.60	0.68
64	29.96	1.24	20.20	2.22	31.07	0.90	20.79	1.98	25.92	0.78
65	27.11	1.64	19.87	2.23	28.89	0.65	20.43	1.88	24.67	0.65
66	27.15	1.47	19.48	2.20	29.29	0.92	20.37	1.64	25.30	0.65

Table A3. Weekly mean soil moisture at 20 cm depth for control and all pavement treatments. S.E.: 1 standard error.

	Treatment									
	Control		IP		PP		IP+		PP+	
Week	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.	Mean	S.E.
1	28.79	1.82	40.14	4.14	45.71	3.97	22.63	2.20	25.27	2.28
2	29.83	1.41	40.30	4.05	45.85	3.91	23.01	2.19	24.45	1.92
3	27.06	1.47	40.08	4.01	44.86	3.92	22.87	2.22	23.62	1.86
4	23.76	1.62	39.84	3.95	43.47	4.14	22.71	2.28	22.75	1.98
5	23.96	2.25	39.52	3.86	42.52	4.24	22.62	2.34	22.33	2.14
6	24.19	2.60	38.68	3.82	41.77	4.12	22.45	2.37	22.25	2.22
7	24.73	2.82	38.34	3.73	43.66	4.13	22.36	2.39	22.24	2.33
8	24.72	3.06	37.66	3.64	42.29	4.14	22.28	2.41	21.75	2.57
9	26.89	2.65	37.14	3.51	41.43	3.62	22.97	2.64	23.69	2.32
10	30.33	1.83	36.87	3.31	41.86	2.87	25.11	2.87	27.81	1.08
11	28.84	2.19	37.54	3.16	41.58	3.14	23.77	2.51	24.76	1.31
12	30.27	2.12	36.52	3.05	40.81	2.71	23.31	2.48	25.37	1.48
13	30.14	2.15	36.30	2.95	39.84	2.78	23.16	2.46	24.42	1.38
14	29.17	2.27	35.75	2.86	37.18	2.85	22.77	2.42	23.27	1.55
15	28.29	2.41	35.39	2.77	36.06	2.91	22.52	2.40	22.53	1.76
16	27.90	2.42	34.82	2.63	35.30	2.60	22.24	2.40	22.10	1.90
17	27.25	2.54	33.44	2.11	35.38	2.07	21.88	2.40	22.42	1.79
18	27.42	2.70	32.80	1.58	34.43	1.85	21.84	2.35	22.35	1.73
19	26.91	2.59	31.53	1.14	33.89	1.66	21.63	2.33	22.48	1.64
25	29.31	1.94	30.06	0.82	37.43	4.30	21.75	2.25	23.96	1.44
26	30.83	1.62	29.91	0.81	37.62	4.31	21.86	2.25	25.29	1.58
27	30.59	1.79	30.24	0.81	37.91	4.66	22.02	2.25	24.48	1.39
28	30.32	1.72	29.93	0.82	37.61	4.47	21.89	2.24	25.01	1.47
29	31.43	1.64	30.23	0.80	37.87	4.22	23.20	2.64	27.70	1.11
30	31.02	1.34	30.36	0.81	37.66	4.23	23.91	2.80	28.58	1.04
31	30.25	1.37	30.52	0.81	37.77	4.62	23.36	2.57	27.55	1.07
32	30.55	1.37	30.73	0.83	37.94	4.50	23.31	2.60	27.30	1.09
33	31.85	1.11	31.34	0.77	38.54	4.30	24.74	2.94	29.48	0.94
34	35.36	1.55	34.68	1.11	41.04	3.90	32.46	3.16	36.22	1.71
35	35.46	1.25	33.48	0.50	37.17	1.57	33.04	2.02	36.22	1.43
36	33.35	1.02	32.16	0.54	35.19	1.50	29.94	2.07	34.68	1.66
37	36.32	0.86	35.05	0.95	37.68	1.43	33.08	0.31	35.80	0.86
38	35.09	0.92	33.67	0.53	36.37	1.09	35.19	1.73	36.34	0.93
39	34.59	1.00	33.10	0.54	35.83	1.36	34.03	1.29	35.66	0.92
40	32.57	1.18	32.56	0.62	35.07	1.34	29.59	0.58	31.94	0.79
41	31.83	1.24	32.34	0.69	34.95	1.39	27.86	0.95	29.69	0.55
42	31.30	1.31	32.06	0.72	35.13	1.58	26.79	1.22	28.51	0.66
43	30.75	1.34	31.99	0.75	35.11	1.62	25.96	1.41	27.39	0.78
44	29.71	1.43	31.90	0.80	35.29	1.71	25.19	1.55	26.43	0.96
45	27.61	1.53	31.56	0.85	35.00	1.79	24.47	1.62	25.67	1.15
46	27.61	1.63	31.32	0.88	35.39	1.81	24.02	1.66	25.92	1.41
47	27.38	1.61	31.27	0.92	34.98	1.74	23.66	1.72	24.89	1.42
48	26.65	1.53	31.09	0.95	34.56	1.60	23.35	1.73	24.48	1.48
49	24.95	1.55	31.57	0.99	34.39	1.44	22.95	1.77	23.71	1.65
50	23.91	1.83	31.14	1.03	33.62	1.24	22.54	1.81	23.00	1.76
51	23.37	2.11	31.16	1.11	33.42	1.12	22.15	1.88	22.26	1.93
52	23.38	2.64	30.92	1.22	33.06	1.06	21.80	1.99	21.64	2.05
53	23.29	2.77	30.46	1.33	33.18	1.32	21.69	1.94	21.58	2.01
54	27.85	2.06	30.11	1.44	35.29	1.84	21.79	1.93	24.11	1.74
55	27.81	2.61	30.86	1.64	35.10	1.74	22.08	1.81	22.68	1.67
56	27.46	2.91	29.91	2.09	34.67	2.29	21.72	2.00	21.58	1.94
57	26.20	3.40	28.56	2.28	33.01	2.69	21.14	2.39	20.31	2.30
58	24.43	3.40	26.88	2.04	30.99	3.00	20.41	2.80	19.53	2.49
59	22.86	3.40	24.96	1.80	25.28	1.22	19.70	3.11	18.67	2.50
60	20.68	3.08	23.25	1.57	22.59	1.67	18.97	3.27	17.66	2.38
61	19.57	2.67	21.36	1.20	21.96	1.69	18.35	3.24	16.33	2.19
62	21.13	2.00	20.37	0.99	24.43	2.68	18.32	3.25	18.41	2.00
63	26.90	1.62	20.56	0.91	27.75	2.26	18.80	3.30	23.29	1.61
64	27.75	1.86	20.94	0.89	28.90	1.28	19.22	3.31	23.57	1.56
65	25.84	2.05	20.35	0.84	26.29	1.28	19.25	3.16	21.81	1.43
66	24.99	1.96	19.95	0.77	25.42	1.38	19.20	3.07	21.97	1.38

Table A4. Contrast 1: Single degree-of-freedom contrast testing the weekly mean soil moisture at various soil depths in control plots against all pavement-covered plots. *** *p* < 0.05**

	5 cm		10 cm		20 cm	
Week	t	p	t	p	t	p
1	2.434	0.026*	1.641	0.117	1.354	0.192
2	3.766	0.001*	1.676	0.110	1.090	0.289
3	5.199	< 0.001*	2.538	0.02*	1.774	0.092
4	6.002	< 0.001*	3.271	0.004*	2.508	0.021*
5	5.893	< 0.001*	3.127	0.006*	2.227	0.038*
6	5.420	< 0.001*	2.884	0.01*	2.013	0.059
7	5.148	< 0.001*	2.555	0.019*	2.026	0.058
8	5.227	< 0.001*	2.437	0.025*	1.795	0.090
9	3.888	0.001*	1.847	0.080	1.365	0.189
10	2.624	0.018*	1.332	0.199	0.961	0.349
11	4.449	< 0.001*	1.999	0.060	1.125	0.275
12	2.416	0.027*	1.258	0.224	0.468	0.645
13	3.650	0.002*	1.495	0.151	0.306	0.763
14	4.559	< 0.001*	1.415	0.173	0.218	0.830
15	4.992	< 0.001*	1.375	0.185	0.310	0.760
16	4.807	< 0.001*	1.328	0.200	0.273	0.788
17	2.694	0.015*	1.203	0.244	0.431	0.672
18	2.899	0.01*	0.848	0.407	0.190	0.851
19	2.042	0.056	0.756	0.459	0.224	0.825
25	1.651	0.116	-0.799	0.435	-0.370	0.716
26	1.515	0.147	-1.539	0.141	-0.797	0.435
27	2.297	0.034*	-0.743	0.467	-0.676	0.507
28	1.916	0.072	-1.164	0.260	-0.616	0.545
29	1.003	0.329	-1.425	0.171	-0.630	0.536
30	1.042	0.311	-1.344	0.196	-0.338	0.739
31	1.418	0.173	-0.954	0.353	-0.162	0.873
32	1.005	0.328	-1.094	0.288	-0.266	0.793
33	0.594	0.560	-1.898	0.074	-0.310	0.760
34	0.382	0.707	-1.629	0.121	0.272	0.788
35	0.409	0.687	-2.428	0.026*	-0.313	0.757
36	0.835	0.415	-1.567	0.135	-0.233	0.818
37	0.314	0.757	-2.417	0.026*	-0.840	0.412
38	0.907	0.376	-1.830	0.084	0.265	0.794
39	1.064	0.301	-1.557	0.137	0.062	0.951
40	1.854	0.080	-0.585	0.566	-0.258	0.800
41	2.270	0.036*	-0.074	0.942	-0.548	0.590
42	2.202	0.041*	0.160	0.874	-0.532	0.601
43	3.128	0.006*	1.063	0.302	-0.472	0.642
44	5.058	< 0.001*	2.577	0.019*	-0.007	0.994
45	6.876	< 0.001*	4.253	< 0.001*	1.002	0.329
46	4.509	< 0.001*	2.917	0.009*	0.932	0.363
47	6.087	< 0.001*	3.403	0.003*	0.797	0.435
48	7.438	< 0.001*	4.145	< 0.001*	1.067	0.299
49	8.663	< 0.001*	5.241	< 0.001*	1.958	0.065
50	8.344	< 0.001*	4.923	< 0.001*	2.139	0.046*
51	7.679	< 0.001*	4.485	< 0.001*	2.104	0.049*
52	7.148	< 0.001*	3.774	0.001*	1.672	0.111
53	6.678	< 0.001*	3.392	0.003*	1.595	0.127
54	3.528	0.003*	0.794	0.438	-0.010	0.992
55	4.692	< 0.001*	1.236	0.232	-0.059	0.954
56	4.752	< 0.001*	1.232	0.234	-0.194	0.848
57	4.070	< 0.001*	0.913	0.373	-0.151	0.882
58	3.284	0.004*	0.554	0.586	0.007	0.995
59	2.594	0.018*	0.562	0.581	-0.253	0.803
60	2.354	0.03*	0.868	0.397	-0.021	0.983
61	1.785	0.091	0.729	0.475	-0.027	0.978
62	-1.449	0.165	-0.282	0.781	-0.307	0.762
63	-2.003	0.060	-2.496	0.022*	-2.037	0.057
64	-1.308	0.208	-3.253	0.004*	-2.280	0.035*
65	-0.763	0.455	-2.114	0.049*	-1.964	0.065
66	-1.324	0.203	-2.147	0.046*	-1.733	0.100

Table A5. Contrast 2: Single degree-of-freedom contrast testing the effect of pavement profile design on weekly mean soil moisture at various soil depths. *** p < 0.05**

	5 cm		10 cm		20 cm	
Week	t	p	t	p	t	p
1	5.752	< 0.001*	5.158	< 0.001*	6.030	< 0.001*
2	5.874	< 0.001*	5.149	< 0.001*	6.446	< 0.001*
3	5.707	< 0.001*	5.073	< 0.001*	6.429	< 0.001*
4	5.375	< 0.001*	4.977	< 0.001*	6.140	< 0.001*
5	4.890	< 0.001*	4.795	< 0.001*	5.788	< 0.001*
6	4.556	< 0.001*	4.427	< 0.001*	5.536	< 0.001*
7	4.019	< 0.001*	4.158	< 0.001*	5.845	< 0.001*
8	3.695	0.002*	3.877	0.001*	5.479	< 0.001*
9	3.746	0.002*	3.679	0.002*	5.263	< 0.001*
10	3.539	0.003*	3.871	0.001*	5.125	< 0.001*
11	4.600	< 0.001*	4.339	< 0.001*	5.980	< 0.001*
12	4.410	< 0.001*	4.558	< 0.001*	5.836	< 0.001*
13	4.311	< 0.001*	4.242	< 0.001*	5.896	< 0.001*
14	4.253	< 0.001*	3.943	< 0.001*	5.476	< 0.001*
15	3.861	0.001*	3.761	0.001*	5.267	< 0.001*
16	3.695	0.002*	3.718	0.001*	5.270	< 0.001*
17	3.593	0.002*	3.874	0.001*	5.468	< 0.001*
18	3.487	0.003*	3.801	0.001*	5.510	< 0.001*
19	3.443	0.003*	4.413	< 0.001*	5.514	< 0.001*
25	3.174	0.005*	3.980	< 0.001*	4.347	< 0.001*
26	2.949	0.009*	3.944	< 0.001*	4.116	< 0.001*
27	3.086	0.006*	3.967	< 0.001*	4.137	< 0.001*
28	2.901	0.01*	4.209	< 0.001*	4.065	< 0.001*
29	2.531	0.021*	3.642	0.002*	3.527	0.002*
30	2.382	0.028*	3.476	0.003*	3.213	0.005*
31	2.641	0.017*	4.102	< 0.001*	3.411	0.003*
32	2.848	0.011*	4.332	< 0.001*	3.603	0.002*
33	2.358	0.03*	3.518	0.002*	3.224	0.004*
34	0.733	0.473	0.455	0.655	1.413	0.174
35	0.322	0.751	-0.045	0.964	0.497	0.625
36	1.581	0.131	1.264	0.222	0.966	0.346
37	1.225	0.236	1.316	0.205	1.919	0.070
38	1.130	0.273	1.183	0.252	-0.708	0.488
39	1.387	0.182	1.389	0.182	-0.360	0.723
40	2.601	0.018*	3.369	0.003*	3.071	0.006*
41	2.844	0.011*	4.122	< 0.001*	4.713	< 0.001*
42	2.868	0.01*	4.314	< 0.001*	5.112	< 0.001*
43	3.107	0.006*	4.657	< 0.001*	5.587	< 0.001*
44	3.440	0.003*	4.764	< 0.001*	5.840	< 0.001*
45	3.405	0.003*	4.818	< 0.001*	5.726	< 0.001*
46	3.433	0.003*	5.425	< 0.001*	5.503	< 0.001*
47	3.448	0.003*	5.542	< 0.001*	5.842	< 0.001*
48	3.715	0.002*	5.957	< 0.001*	6.019	< 0.001*
49	3.861	0.001*	6.234	< 0.001*	6.433	< 0.001*
50	3.763	0.002*	5.568	< 0.001*	6.117	< 0.001*
51	3.843	0.001*	5.723	< 0.001*	5.971	< 0.001*
52	3.807	0.001*	5.012	< 0.001*	5.400	< 0.001*
53	3.921	0.001*	4.831	< 0.001*	5.153	< 0.001*
54	3.577	0.002*	4.961	< 0.001*	5.334	< 0.001*
55	3.462	0.003*	4.951	< 0.001*	5.392	< 0.001*
56	3.034	0.007*	4.397	< 0.001*	4.568	< 0.001*
57	2.254	0.037*	3.767	0.001*	3.717	0.001*
58	1.892	0.075	3.303	0.004*	3.181	0.005*
59	1.490	0.154	2.819	0.011*	2.254	0.037*
60	1.217	0.239	2.342	0.031*	1.817	0.086
61	0.981	0.340	2.093	0.051	1.924	0.070
62	0.618	0.544	1.710	0.104	1.801	0.088
63	0.584	0.567	0.250	0.805	1.575	0.133
64	0.847	0.408	1.446	0.165	1.864	0.079
65	0.937	0.361	1.130	0.273	1.494	0.153
66	0.957	0.352	1.007	0.327	1.159	0.262

Table A6. Contrast 3: Single degree-of-freedom contrast testing the effect of pavement type on weekly mean soil moisture at various soil depths. *** *p* < 0.05**

	5 cm		10 cm		20 cm	
Week	t	p	t	p	t	p
1	0.542	0.595	0.068	0.947	1.305	0.208
2	0.177	0.862	-0.261	0.797	1.163	0.259
3	-0.052	0.959	-0.383	0.706	0.925	0.367
4	-0.383	0.706	-0.501	0.622	0.596	0.558
5	-0.341	0.737	-0.598	0.557	0.423	0.677
6	-0.293	0.773	-0.630	0.536	0.448	0.660
7	-0.065	0.949	-0.670	0.511	0.814	0.426
8	-0.153	0.880	-0.819	0.423	0.625	0.540
9	0.071	0.944	-0.658	0.519	0.827	0.419
10	0.308	0.762	-0.342	0.736	1.529	0.144
11	-0.646	0.527	-0.685	0.501	0.982	0.339
12	-0.167	0.869	-0.252	0.804	1.294	0.212
13	-0.656	0.520	-0.670	0.511	0.991	0.335
14	-1.296	0.211	-0.987	0.336	0.394	0.698
15	-1.598	0.127	-1.105	0.283	0.136	0.893
16	-1.496	0.152	-0.904	0.377	0.070	0.945
17	-0.770	0.452	-0.451	0.657	0.554	0.587
18	-1.005	0.328	-0.528	0.603	0.512	0.615
19	-0.412	0.685	0.327	0.748	0.831	0.416
25	0.991	0.335	1.612	0.124	1.913	0.071
26	1.562	0.136	2.403	0.027*	2.248	0.037*
27	0.550	0.589	1.551	0.138	1.936	0.068
28	1.361	0.190	2.396	0.028*	2.125	0.047*
29	1.605	0.126	2.886	0.01*	2.491	0.022*
30	1.422	0.172	2.827	0.011*	2.476	0.023*
31	0.869	0.396	2.529	0.021*	2.247	0.037*
32	0.985	0.338	2.495	0.023*	2.234	0.038*
33	1.144	0.267	2.602	0.018*	2.459	0.024*
34	0.728	0.476	1.415	0.174	2.030	0.057
35	0.639	0.531	1.649	0.117	2.454	0.024*
36	0.460	0.651	1.504	0.150	2.756	0.013*
37	-0.400	0.694	1.107	0.283	2.670	0.015*
38	-0.389	0.702	1.337	0.198	1.824	0.084
39	-0.417	0.682	1.292	0.213	2.068	0.053
40	-0.744	0.467	1.205	0.244	2.446	0.024*
41	-0.807	0.430	1.256	0.225	2.148	0.045*
42	-0.607	0.551	1.352	0.193	2.064	0.053
43	-0.730	0.475	1.173	0.256	1.845	0.081
44	-0.786	0.442	1.084	0.293	1.740	0.098
45	-0.926	0.367	1.003	0.329	1.616	0.123
46	-0.305	0.764	1.689	0.109	1.959	0.065
47	-0.645	0.527	1.352	0.193	1.631	0.119
48	-0.508	0.618	1.481	0.156	1.553	0.137
49	-1.082	0.293	1.067	0.300	1.195	0.247
50	-1.290	0.214	0.724	0.479	0.935	0.362
51	-1.257	0.226	0.758	0.458	0.702	0.491
52	-1.056	0.306	0.769	0.452	0.519	0.610
53	-0.800	0.435	1.154	0.264	0.661	0.516
54	0.050	0.961	2.601	0.018*	2.049	0.055
55	-1.026	0.318	1.707	0.105	1.231	0.233
56	-0.939	0.360	2.087	0.051	0.990	0.335
57	-1.036	0.314	1.682	0.110	0.671	0.510
58	-0.662	0.516	1.459	0.162	0.572	0.574
59	-0.480	0.637	1.167	0.259	-0.133	0.895
60	-0.382	0.707	0.897	0.381	-0.388	0.703
61	0.015	0.988	1.014	0.324	-0.317	0.755
62	1.811	0.087	3.536	0.002*	0.924	0.367
63	3.334	0.004*	3.331	0.004*	2.952	0.009*
64	3.005	0.008*	5.078	< 0.001*	3.259	0.004*
65	2.577	0.019*	4.099	< 0.001*	2.279	0.035*
66	2.976	0.008*	4.776	< 0.001*	2.272	0.036*

Table A7. Contrast 4: Single degree-of-freedom contrast testing the interaction of pavement type and profile design on weekly mean soil moisture at various soil depths. *** *p* < 0.05**

	5 cm		10 cm		20 cm	
Week	t	p	t	p	t	p
1	-0.388	0.703	-0.752	0.461	0.464	0.648
2	-0.216	0.832	-0.683	0.503	0.686	0.501
3	-0.161	0.874	-0.635	0.533	0.675	0.508
4	-0.234	0.818	-0.650	0.523	0.583	0.567
5	-0.069	0.946	-0.665	0.514	0.514	0.613
6	-0.109	0.914	-0.750	0.462	0.508	0.617
7	0.099	0.922	-0.878	0.391	0.851	0.406
8	0.086	0.932	-0.898	0.380	0.785	0.443
9	0.151	0.882	-1.016	0.322	0.588	0.564
10	0.427	0.675	-0.845	0.408	0.455	0.655
11	-0.077	0.940	-1.080	0.294	0.594	0.560
12	-0.455	0.655	-1.223	0.236	0.453	0.656
13	-0.297	0.770	-1.159	0.261	0.470	0.644
14	-0.361	0.722	-1.240	0.230	0.187	0.854
15	-0.127	0.900	-1.202	0.244	0.132	0.896
16	0.081	0.936	-1.064	0.301	0.126	0.901
17	0.166	0.870	-0.962	0.348	0.312	0.759
18	0.592	0.561	-0.963	0.348	0.269	0.791
19	0.724	0.478	-0.548	0.590	0.389	0.702
25	1.342	0.196	0.126	0.901	1.028	0.317
26	1.203	0.245	-0.009	0.993	0.865	0.398
27	1.355	0.192	0.108	0.915	0.994	0.333
28	1.108	0.283	-0.122	0.904	0.899	0.380
29	1.168	0.258	0.084	0.934	0.644	0.527
30	1.307	0.208	0.318	0.754	0.544	0.593
31	1.138	0.270	0.276	0.786	0.601	0.555
32	1.244	0.230	0.341	0.737	0.643	0.528
33	1.439	0.167	0.453	0.656	0.507	0.618
34	1.273	0.219	0.842	0.411	0.522	0.607
35	1.140	0.269	0.573	0.574	0.185	0.856
36	0.761	0.457	0.485	0.633	-0.607	0.551
37	0.753	0.461	0.511	0.616	-0.049	0.962
38	0.838	0.413	0.845	0.409	0.731	0.474
39	0.562	0.581	0.771	0.451	0.522	0.607
40	0.485	0.634	0.337	0.740	0.079	0.938
41	0.414	0.684	0.284	0.779	0.375	0.712
42	0.326	0.748	0.288	0.776	0.582	0.568
43	0.380	0.708	0.284	0.780	0.683	0.503
44	0.573	0.573	0.267	0.793	0.807	0.430
45	0.689	0.500	0.117	0.908	0.779	0.446
46	0.597	0.558	-0.027	0.979	0.713	0.485
47	0.605	0.553	0.013	0.990	0.822	0.421
48	0.790	0.440	-0.071	0.944	0.795	0.437
49	0.659	0.518	0.020	0.984	0.688	0.500
50	0.426	0.675	0.304	0.765	0.646	0.526
51	0.468	0.645	0.388	0.702	0.639	0.530
52	0.629	0.538	0.631	0.536	0.605	0.552
53	0.731	0.475	0.749	0.463	0.719	0.481
54	0.269	0.791	0.474	0.642	0.781	0.444
55	0.473	0.642	0.634	0.534	0.923	0.368
56	0.165	0.871	1.063	0.302	1.051	0.307
57	-0.035	0.973	1.133	0.272	0.976	0.342
58	0.039	0.969	1.015	0.324	0.885	0.387
59	0.209	0.837	0.908	0.376	0.257	0.800
60	0.440	0.665	0.787	0.441	0.129	0.899
61	0.690	0.499	0.732	0.474	0.586	0.565
62	0.668	0.513	1.105	0.284	0.884	0.388
63	0.815	0.425	0.408	0.688	0.683	0.503
64	1.059	0.303	1.825	0.085	0.957	0.352
65	1.091	0.290	1.477	0.157	0.906	0.377
66	0.904	0.379	1.579	0.132	0.748	0.464

Appendix B – Effect of Pavement on Evaporation

Though evaporation was not initially measured at the experimental site, it was subsequently deemed an important component of the hydrological cycle. A trial was set up with the intention of understanding how evaporation is affected by both porous and impervious pavements, relative to bare soil. Fifteen cubic plastic pots of side length 30cm were half-filled with kiln-dried soil collected from the experimental site. The tare weights of each pot and soil was determined before being filled with water to the point of saturation (the surface of the soil was glistening, but not submerged beneath water) and reweighed such that the mass of water was known in each pot. Each of the pots was then randomly assigned to one of 3 treatments: a) control - the pot was left as is; b) the soil was covered with a 10 cm deep porous pavement; or c) the soil was covered with a 10 cm deep impervious pavement. All pavement covers were pre-cast to fit inside the edges of the plastic pot, with a 1mm gap between the edge of the pavement and pot. All pots were then placed in a controlled environment room with a constant temperature of 25°C and relative humidity of 45%. Pots were weighed daily, at first, then periodically to determine water loss resulting from evaporation. Results are shown below as the percentage of initial water content lost to evaporation.

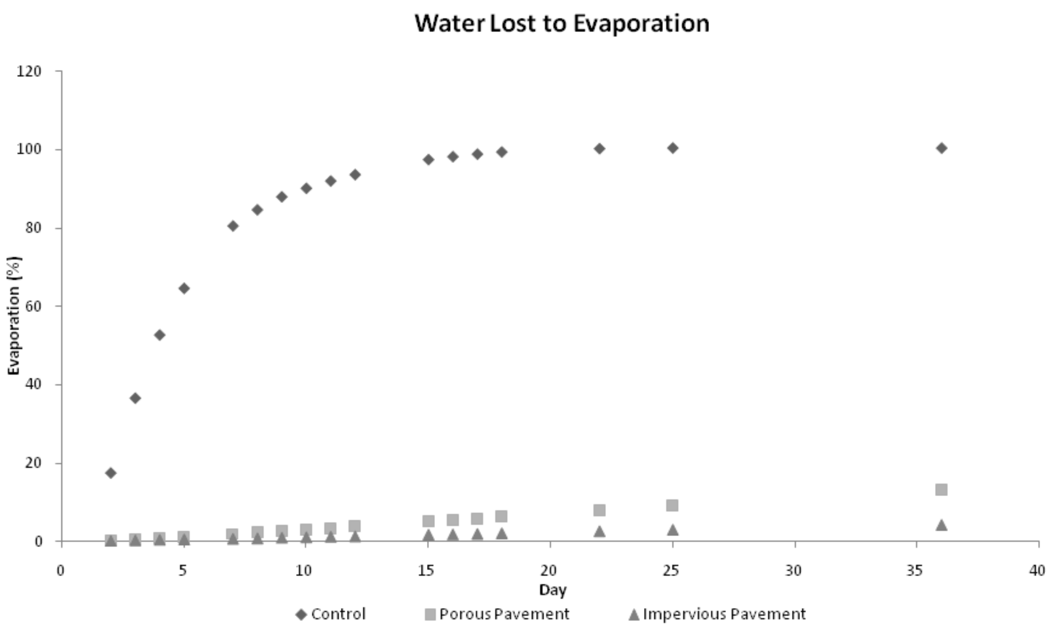

Figure B1. Percentage of initial water content lost to evaporation during the course of 36 days for bare soil (control) and two pavement types.

Evidently, the evaporation of soil moisture from control plots initially occurs quickly, then decreases as the remaining soil water is bound more tightly by capillary forces, and the soil's hydraulic conductivity rapidly decreases. In contrast, the evaporation of soil moisture from both pavement treatments is very slow, likely buffered from atmospheric demand. It was assumed that the large pores in porous paving would allow greater evaporation than impervious pavements. Surprisingly, no substantial differences in evaporation rate are evident between pavement types. It is believed that the large pores can 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 is negligible.

Appendix C – Testing the Steel Rod Method for Measuring Soil Aeration

To test the validity of the steel rod method (Carnell and Anderson 1986) for measuring soil aeration in this experiment, steel rods were inserted into a subset of the plots. The results of this initial test would determine if the method would be used the following year to assess soil aeration during spring and summer. On 4 December 2007, fifteen rods were allocated evenly amongst three treatments (control, PP, IP) and inserted into soils of fifteen plots following the method of Hodge et al. (1993). Rods were inserted halfway between the centre and edge of each plot. On 6 March 2008, all rods were unearthed, cleaned, and swabbed in an ammonia solution to stop oxidation. Following Carnell and Anderson (1986), two corrosion categories were created: 1) red/brown rust or raised black corrosion, which indicated well aerated soil; and 2) smooth black or matte grey corrosion indicative of anaerobic conditions, or shiny metal, both classed as inhospitable for root growth. Using these categories, the corrosion patterns were analysed and scores reflecting the proportion of rust were assigned to each 12 cm segment of rod based on the method of Hodge and Boswell (1993). The data showed that anaerobic scores were distinctly lower in unpaved soils than in paved soils (Figure C1). However, large variation around mean anaerobic scores resulted in only a few statistically significant differences (Table C1).

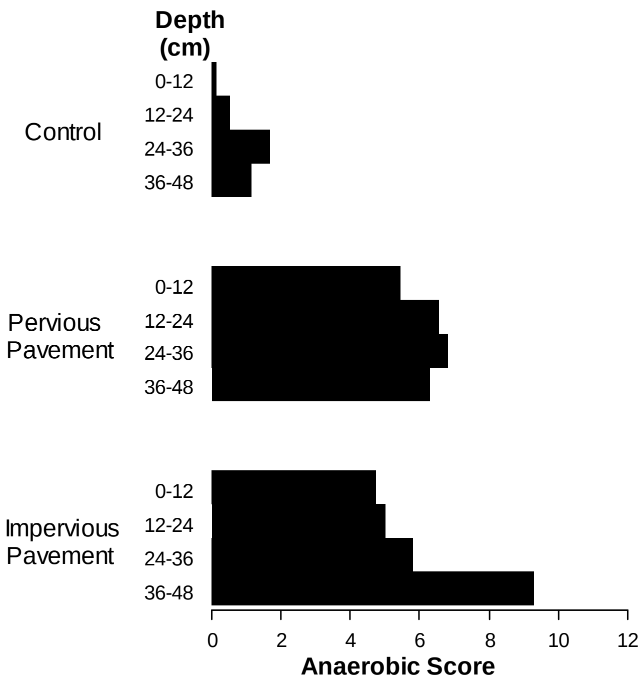

Figure C1. Evaluation of soil aeration. The mean anaerobic score (n=5) for all treatments stratified by depth beneath the soil surface. Greater anaerobic score corresponds to decreased soil oxygen. Control plots exhibit greater aeration than soil beneath pavement.

Aeration data for this test period were analysed via two-way ANOVA to contrast differences between treatments and depth classes for soil aeration data. Subsequent pairwise comparisons were computed by the Tukey-Kramer HSD test. The data confirmed that aeration within treatments was independent of soil depth; anaerobic scores were statistically similar throughout the soil profile within all treatments. However, soil aeration did differ amongst treatments within depth classes. In the uppermost soil layer, anaerobic scores were significantly lower in control plots than in either paved treatment. The only other statistically significant difference occurred in the deepest soil layer where impervious pavement resulted in lower aeration than control plots.

Table C1. Mean anaerobic scores and standard errors during summer 2008. Significant differences resulting from treatment are noted by different symbols following the mean value. (p=0.05)

	Depth below ground (cm)			
Treatment	**0-12**	**12-24**	**24-36**	**36-48**
Control	*0.15 (0.22)^{a}*	*0.55 (0.82)^{a}*	*1.70 (1.87)^{a}*	*1.15 (1.42)^{a}*
Porous Pavement	*5.45 (1.85)^{b}*	*6.55 (2.58)^{a}*	*6.80 (2.67)^{a}*	*6.30 (2.51)^{ab}*
Impervious Pavement	*4.75 (2.22)^{b}*	*5.00 (2.66)^{a}*	*5.80 (2.63)^{a}*	*9.30 (1.98)^{b}*

Encouraged by the simplicity of the method as well as the ability to determine relative treatment and depth differences, the method was adopted for two subsequent measurement periods.

Appendix D – Record of Achievements

The author's efforts to complete this thesis were temporarily derailed in an attempt to develop the skills necessary to be successful in academia. In particular, the author published papers in peer-reviewed international journals and presented at local and international conferences.

Peer-reviewed publications:

1. Morgenroth, J. 2011. Root Growth Response of *Platanus orientalis* to Porous Pavements. Arboriculture and Urban Forestry 37(2): 45-50.
2. Morgenroth, J., and R. Visser. 2011. Above-Ground Growth Response of *Platanus orientalis* to Porous Pavements. Arboriculture and Urban Forestry 37(1): 1-6.
3. Morgenroth, J., and G.D. Buchan 2009. Soil Moisture and Aeration Beneath Pervious and Impervious Pavements. Arboriculture and Urban Forestry 35(3): 135-141.
4. Morgenroth, J. 2008. A review of root barrier research. Arboriculture and Urban Forestry 34(2): 84-88.

Conference presentations:

1. New Zealand Arboricultural Association Conference. 11-13 November 2010. Auckland, New Zealand. Presentation title: "Installing Porous Pavements".
2. International Conference for Urban Forestry in Challenging Environments. 29 Aug - 1 Sept 2010. Beijing, China. Presentation title: Porous Pavements increase above-ground growth of Platanus orientalis".
3. International Society of Arboriculture Annual Conference. 25-29 July 2009. Providence, Rhode Island, USA. Presentation title: "*Effect of Porous Paving on Tree Growth*".
4. The Landscape Below Ground III. 6-8 October 2008. Lisle, Illinois, USA. Presentation title: "*Response of urban trees to changes in soil moisture and aeration status as affected by porous paving*".
5. New Zealand Institute of Forestry Conference. 15-18 May 2008. Presentation title: "*Urban Forests: overlooked and underappreciated"*.
6. New Zealand Arboricultural Association Conference. 22-24 November 2007. Christchurch, New Zealand. Presentation title: "*Minimizing tree root conflicts with infrastructure while optimizing the rooting environment for urban trees***".**