# EFFECT OF PERVIOUS AND IMPERVIOUS PAVEMENT ON THE RHIZOSPHERE OF AMERICAN SWEETGUM (*Liquidambar styraciflua)*

A Thesis

by

BHAVANA VISWANATHAN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2010

Major Subject: Horticulture

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Approved by:

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| Chair of Committee, | Astrid Volder |
| Committee Members, | Jacqueline Aitkenhead Peterson |
| | Wesley Todd Watson |
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# ABSTRACT

Effect of Pervious and Impervious Pavement on the Rhizosphere
of American Sweetgum (*Liquidamabar styraciflua*). *(*May 2010)

Bhavana Viswanathan, B.Sc., University of Madras; M.Sc., University of Madras
Chair of Advisory Committee: Dr. Astrid Volder

Mature trees help to offset urban area problems caused by impervious pavement. Trees in paved areas remain unhealthy due to a poor root zone environment. The objective of this experiment was to test if soil under pervious concrete, with greater water and gas infiltration, would be more beneficial to existing mature trees during urban development. Root activity, root growth and soil chemistry of American sweetgum under standard concrete, pervious concrete and no concrete were measured. Soil $CO_2$ efflux rates and soil $CO_2$ concentrations were extremely high under both concrete treatments. Soil under standard concrete had lower oxygen concentrations than soil under pervious concrete and control treatments, particularly under wet conditions. There was no pavement effect on soil water content or soil chemistry. Under control treatment standing live root length was greater than under both concrete treatments. There were no major differences in soil conditions between impervious and pervious concrete treatments. The soil under the plots, a Ships clay, with very low permeability may have prevented soil water infiltration. Likely this overrode any potential treatment effects due to porosity of the concrete. To obtain root zone benefits out of pervious concrete, a different base soil with a higher permeability would be a better alternative.

# DEDICATION

I dedicate my Master of Science thesis to my paternal grandfather, the late Mr. P. S. Ramachandran. His simplicity and straightforward approach to life will always be a source of inspiration for me.

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Last, but not least, I would like to thank my parents for their deep and unconditional support and encouragement all through my life.

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# CHAPTER I

# INTRODUCTION AND LITERATURE REVIEW

## The urban environment

Increasing rates of urbanization affect the functioning of the environment. A high population density in urban areas ultimately results in human manipulation of the environment to suit their needs. One such manipulation is the construction of paved impervious areas. Impervious surfaces are areas paved with standard concrete or asphalt mixtures that do not allow the passage of gaseous or fluid materials through them. Impervious areas have increased in urban areas (Khan 2005). For example, in the city of Houston, Texas, concrete and asphalt covered surfaces have increased in area by 21% from 1984 to 1994, 39% from 1994 to 2000 and 114% from 2000 to 2003 as the city has grown (Khan 2005). The presence of these impervious surfaces enhances heat stress (Yuan and Bauer 2007), reduces water infiltration (and hence lower soil moisture content), increases stormwater runoff (Erickson and Stefan 2009), raises temperature in surface water bodies (Yalcin and Yetemen 2009), and degrades soil quality (soil compaction, less aeration, greater soil strength) (Jim 1998) which could potentially affect the urban physical environment and in turn the vegetation, animals and human beings living in it.

Urban areas have greater temperatures due to greater absorption of short-wave radiation by low-albedo surfaces such as buildings and pavements (Asaeda et al. 1996)

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This thesis follows the style of Plant and Soil.

and reduced evaporative cooling rates compared to rural areas due to reduced latent heat exchange. Anthropogenic emissions through combustion engines, electrical equipment and use of electrical appliances also increase urban temperatures (Hart and Sailor 2009). Paved surfaces such as asphalt and concrete have a greater capacity for heat absorption than unpaved surfaces (Herb et al. 2008) and much of the energy absorbed by paved surfaces is transferred to the atmosphere and contributes to atmospheric heating. The phenomenon of higher temperatures in urban areas compared to the surrounding rural areas is called the “urban heat island” (UHI) effect (Voogt and Oke 2003).

The urban heat island is generally more pronounced at night. When there is no solar radiation input, all surfaces lose heat energy to the atmosphere, but urban areas with more constructed buildings and paved areas lose heat energy at a slower rate than rural areas since released energy is often reabsorbed by building structures and then re-released. Impervious pavement not only loses heat to the atmosphere but some of the heat is also transferred to the soil beneath. The soil beneath asphalt and concrete has been shown to be considerably warmer than soil beneath vegetative surfaces (Montague and Kjelgren 2004). Rhizosphere temperatures in an asphalt parking lot in Arizona were 15°C higher than below turfgrass surfaces (Celestian and Martin 2003). In New Brunswick, NJ, 2.5 m by 2.5 m tree planter boxes were cut into the asphalt of a parking lot. Near the center of the planter spaces, at depths of 15 cm and 85 cm from the edge of the asphalt the maximum soil temperature exceeded controls by up to 3 ºC; at the same depth but below the asphalt, maximum temperatures exceeded controls by up to 10 ºC.

However, temperatures below the asphalt ranged from 0.5 ºC to 34.2 ºC, which was well within the toleration of tree roots (Halverson and Heisler 1981).

Urban soils are characterized by high bulk densities, low soil moisture content, poor organic matter input, high soil strength, poor aeration and low porosity (Jim 1998). A survey of urban soils in Hong Kong showed that there were no surface organic or minero-organic layers in Hong Kong urban soils. However, there was an artificial layering due to dumping of fill materials (Jim 1998). Hong Kong urban soils also had a low water-holding capacity along with a low nutrient supply and a low rate of nutrient replenishment (Jim 1998). Sealing these soils with impermeable concrete would reduce organic matter input which leads to reduction in mineralization rates and nutrient availability.

Compaction is another cause of urban soil degradation. Compaction can originate from the use of heavy equipment during development. The use of motorized vehicles or compaction can furthermore be deliberate as a way to support urban structures and pavements. When pavements are placed, the technique requires the soil to be compacted before placing the concrete or asphalt and hence soil becomes high in bulk density and soil strength. Sometimes compaction can even be caused by intense human pedestrian traffic. For example, in a public park in Tel Aviv, Israel, human traffic in a high visitor's pressure area reduced soil penetration depth 20-40 times when compared to that of a low visitor's pressure area. Visitors' pressure reduced soil moisture and organic matter content as well (Sarah and Zhevelev 2007). Motor traffic can also cause soil compaction. A wide tire with contact pressure of 250-450 kPa on wet soil or under higher contact pressures of 500 kPa compacted not only top soil but the subsoil layer as well (Hadas 1994). Compaction increases soil strength which increases resistance to root penetration (Taylor and Brar 1991). Compaction also leads to decreased oxygen diffusion, particularly when volumetric water content increases and the smaller pores become filled with water. Reduced oxygen diffusion reduces the ability of plants to maintain root growth  (Taylor and Brar 1991). Some species are able to penetrate compacted soils when wetting of the soil reduces soil strength. These are generally species that are native to riparian areas and have an increased tolerance to flooded conditions that reduce oxygen availability in the soil. (Day et al. 2000) suggest that this partially explains the success of many species native to riparian areas in urban environments.

Compacted soils also affect urban hydrology. Compacted soils reduce water infiltration and lead to greater stormwater runoff (Pitt et al. 2008). The use of impervious pavements in urban areas adds to this problem. When soils are covered with impervious concrete there is less water infiltration and more stormwater runoff. The lack of water infiltration increases peak flow rates in nearby surface waters during storms, while reducing stream base flow rates in between storms. For example, in Atlanta from 1958 to 1996 peak flows were 30 % - 100 % greater and recession periods following peak flow were considerably shorter for urban areas compared to rural areas (Rose and Peters 2001). Similarly, in the Vermillion river watershed in Minnesota, increase of impervious area from 4.9 % to 18.3 % decreased groundwater recharge by 30 % to 40 % in a year (Erickson and Stefan 2009). As the ground water table drops, the volume of water during baseflow also reduces and can sometimes be non-existant.  Enhanced peak flow rates cause stream bank erosion, while reduced base flow rates and reduced groundwater recharge exacerbate the effects of drought and reduce the health and function of urban riparian zones.

Chemical quality of runoff is affected by increases in impervious surface cover (Praskievicz and Chang 2009). Materials and particles collected on impervious surfaces are swept into stormwater systems during storm events. These particles get carried into stormwater inlets and eventually into a downstream water channel. For example, in a freshwater creek in North Carolina, land use and impervious surface cover were positively correlated with concentration of pollutants such as orthophosphate and surfactants which in turn were responsible for an increase in biochemical oxygen demand (BOD), Stream contaminant concentrations were highest in urban runoff compared to suburban and rural runoffs. Contaminant concentrations were also higher just after a rain event (Mallin et al. 2009). The pollution in urban stormwater runoff can be substantial. For example, the main pollutants in urban runoff in the Atlanta area were total suspended solids (TSS) and chemical oxygen demand (COD). The first 30% of the runoff volume carried 34.7% - 69.6% TSS and 43.6% - 54% COD, 17.1% – 41% total nitrogen and 24.4% - 60.8% total phosphorus (Luo et al. 2009). In Bergen, Norway, stormwater runoff from impervious surfaces was contaminated with polychlorinated biphenyls (PCB), poly aromatic hydrocarbons (PAH), Pb and Zn (Jartun et al. 2008). Impervious surface areas therefore not only affect the hydrology of local water channels but also the chemistry.

Impervious surfaces elevate the temperature of water in urban streams and lakes. When water runs off an impervious surface, the heat from the impervious surface is transferred to the water raising the temperature of the receiving water. For example, in Istanbul, Turkey, ground water temperatures in an urban site were 2.5 ºC higher than at rural sites (Yalcin and Yetemen 2009). This heating up of stormwater runoff could lead to unsuitable environments for aquatic life in lakes and streams. Plants and animals originally adapted to coldwater habitats may be unable to survive as temperature in their habitat increases. Higher water temperatures also lead to reduced oxygen availability in the water and can cause algae to proliferate (Wagner and Adrian 2009). Runoff from parking lots was found to have a significant negative effect on fish assemblages in creeks in Mississippi (Albanese and Matlack 1999). Thus, impervious surfaces lead to greater peak flows, reduced ground water recharge, greater stream pollution and higher surface water temperatures, which call for alternative pavement options that would alleviate these disadvantages by allowing infiltration of water into the soil.

## The role of trees in the urban environment

Trees shade surrounding surfaces and reduce the amount of direct radiation reaching the surface, soil or pavement, thus preventing heating of that surface. The larger the canopies of street trees, the greater the cooling achieved (Shashua-Bar et al. 2010). Planting trees beside buildings keeps the temperature of buildings lower and reduces air cooling costs. For example, temperature reductions through shading by trees were 40 % in urban areas and 30 % in rural areas and savings in heating and cooling costs ranged from $30 - $180 in urban and $60 - $400 in rural areas (Akbari and Taha 1992). However, it is not the shading alone that cools the environment. A shade-mesh giving the same amount of shade as urban garden trees did not provide the same cooling (Shashua-Bar et al. 2009). Thus, the combination of transpirational cooling and shading is necessary to gain the greatest cooling benefit from urban trees.

Transpirational cooling is an important contribution to the reduction of UHI. During the day, trees draw water through the roots and transpire it back to the atmosphere through leaf stomata. The conversion of liquid water to water vapor is very energy intensive and thus, when water evaporates from the leaves, the surrounding air is cooled. For example, in urban gardens the presence of trees was found to lower the air temperature by 3 ºC to 4 °C in hot humid weather where maximum temperatures ranged between 24 ºC to 30 ºC (Shashua-Bar et al. 2010). In addition, trees were found to be more effective in cooling the environment per unit of water lost when compared to grass (Shashua-Bar et al. 2009), probably because tall trees provide additional shading benefits. Cooling effects are not limited to the immediate environment of the vegetation. Urban green areas that were 60m wide were found to have a significant cooling effect almost 100m beyond the area boundary (Shashua-Bar and Hoffman 2000). Thus planting trees can be highly beneficial in cooling urban areas, both through shading and the process of evaporative cooling.

Trees help to remove air borne pollution. Pollutants are removed by trees through the interception of airborne particles (Nowak et al. 2006). Removal of air pollutants by trees was 312.03 Mg in Guangzhou, China in 2000 (Jim and Chen 2008). When tree cover was extensive and continuous, it enhanced pollutant removal (Jim and Chen 2008).

Trees take in $CO_2$ and release $O_2$ through the process of photosynthesis. They therefore have the capacity to act as a carbon sink and help offset increasing $CO_2$ levels in the atmosphere. Modeling studies have shown that in Canada boreal forests and old black spruce act as carbon sinks (Sun et al. 2008). Field studies with boreal Scots pine forests showed that they acted as a carbon sink each year over a period of 10 years (Ilvesniemi et al. 2009). In urban areas, human modified landscapes have been shown to have larger carbon pools than surrounding undeveloped areas in a semi arid grassland region in Colorado (Golubiewski 2006).

Trees also help in urban water management. Since trees draw water through their roots, they reduce standing water in the soil. Dying tree roots also leave macropores in the soil that improve water holding capacity and water infiltration. Thus, planting and preserving trees will help reduce stormwater run-off, while removing trees reduces the capacity to retain and detain stormwater. For example, a 20% decrease in tree cover resulted in a $2 \times 10^{10}$ cubic meter increase in stormwater runoff in Atlanta (Soltis 1997), while a detailed analysis on Chamblee, Georgia, showed that a 44% decrease in vegetation would result in $14 million expenditure to build containment facilities for stormwater retention (de Luna et al. 2000).

Thus, trees in urban areas help to reduce air temperatures, air pollution, act as carbon sinks and reduce urban hydrological problems. However, trees planted in paved areas are subject to many environmental stresses typical of the urban environment – excess heat, extremes in water availability, compacted soils and less fertile soils. Even when pits filled with rich top soil for tree planting are provided within the paved areas, the compacted subsoil underneath and around the root ball affects root growth and establishment. The lack of water infiltration into the soil surrounding the roots also causes significant drought stress. Thus, there is a need for an alternative surface covering that allows for human traffic without the need for soil compaction and still allows for water infiltration and ground water recharge. One option would be the use of pervious pavements that support light duty traffic, while retaining permeability to water and air.

## Pervious concrete

Pervious concrete surface is a concrete paved surface that allows gaseous or fluid material to pass through them by means of pores. Pervious concrete is made up of the same material as impervious concrete but the fine particles are omitted and the size distribution of coarse aggregates (gravel or crushed stone) is kept narrow (Tennis et al. 2004). Pervious concrete usually attains a void of 15% - 25%, allowing for a water flow rate of around 200L $m^{-2}$ $min^{-1}$ or higher (Tennis et al. 2004). Pervious concrete densities range from 1600 kg $m^{-3}$ to 2000 kg $m^{-3}$. The primary application of this concrete is as pavement, however, the porosity of pervious concrete finds its application in reducing stormwater runoff, and in areas such as parking lots, drainage media for hydraulic structures, tennis courts, and greenhouses (Tennis et al. 2004). Pervious concrete can store stormwater temporarily before it infiltrates into the base layer. A 125 mm thick pavement layer with 20% voids can store 25mm of a sustained rainstorm and when placed on a 150 mm thick open graded gravel/crushed rock sub-base, can store up to 75 mm of precipitation (Tennis et al. 2004).

Pervious concrete considerably reduced peak flows after a rain event in comparison to other permeable pavement systems and impervious pavements (Collins et al. 2008). In a study in a permeable pavement parking lot in North Carolina, pervious concrete had the least total runoff compared to permeable corrugated grid pavers (CGP), permeable interlocking grid pavers (PICP) and impervious asphalt while peak flow and runoff were highest for asphalt (Collins et al. 2008). Thus pervious concrete may be a better alternative compared to other permeable pavement systems in reducing stormwater runoff and allowing for infiltration.

The lifespan of a pervious concrete surface depends on the porosity of the media and the rate at which pores become clogged in their environment of use (Scholz and Grabowlecki 2007). Pervious pavement is prone to clogging and once totally clogged will have to be removed and replaced. With pervious pavements on highways, clogging was found to be due to one of the following reasons: 1) sediments that are pushed into pores by moving traffic before they are washed off by rain 2) waterborne sediments which clog the pores and 3) collapsing pores due to shear stress caused by vehicles breaking at the same spot (Scholz and Grabowlecki 2007). Situating permeable pavements near areas of soil disturbance also reduces infiltration rates in pervious concrete (Bean et al. 2007b). Pervious concrete can get clogged with clay and other small particles during extreme storm events but most of this material is likely to remain near the surface and could be removed using simple maintenance procedures (Haselbach 2010; Sansalone et al. 2008). The water infiltration rates after maintenance are generally slightly lower than the initial rates of water infiltration (Haselbach 2010).

## Soil processes

A healthy root zone environment with optimum moisture, oxygen and soil characteristics generally results in greater root and microbial activity. Respiratory activity of roots and microbes releases $CO_2$ in the soil environment and this $CO_2$ is released into the atmosphere as a function of the $CO_2$ concentration difference between the soil and the air (i.e. diffusion). The rate of $CO_2$ efflux from the soil is known as soil respiration. Soil respiration is the combined effect of 1) root and rhizospheric respiration and 2) microbial respiration.

Several studies have attempted to quantify the relative importance of the root and heterotrophic fractions of soil $CO_2$ efflux. In a study in a coniferous forest in Oregon, organic litter decomposition accounted for 77% while root respiration accounted for the remaining 23% (Sulzman et al. 2005). In contrast, in a mixed harwood deciduous forest in Massachussets where live root respiration accounted for 33% of annual soil $CO_2$ flux (Bowden et al. 1993). In an impervious paved system, the absence of aboveground organic litter input would likely reduce microbial decomposition rates and thus overall $CO_2$ efflux rates from the soil. The scenario might be slightly different for pervious pavements where canopy and stem flow increase soil moisture and some aboveground litter fractions may still enter the soil. Furthermore stemflow contributes to the soil C pool by introducing dissolved organic carbon to the soil (Liu and Sheu 2003). Stemflow flux of DOC at 132.4 kg $ha^{-1}$ in Chinese fir plantations was much higher than stemflow in hardwood stands which ranged between 15.3 and 6.7 kg $ha^{-1}$ (Liu and Sheu 2003).

Soil respiration is also affected by soil moisture, soil temperature and oxygen availability. Lack of soil water availability or excess of soil water availability is one of the most important factors affecting soil respiration. For example, in a temperate forest ecosystem in Germany, drought reduced summer soil respiration in beech by 30% and spruce by 50% between the summer of 2002 and 2003 (Nikolova et al. 2009). In a $^{13}C$ labeling study, reduced photosynthetic C fixation due to drought resulted in decreased soil respiration rates as less carbon was allocated to the roots (Ruehr et al. 2009). Drier conditions do not always reduce soil respiration however, in waterlogged soils at a site in Great Britain, soil drying increased soil respiration and plant production (Sowerby et al. 2008). Waterlogged soils have low oxygen concentration and low biological activity and drought stimulated aeration and in turn biological activity. Plant growth and microbial activity both increased, with a consequent increase in soil respiration (Sowerby et al. 2008). At a mesic site, however, drought became a limiting factor and decreased biological activity (Sowerby et al. 2008). Thus, both dry and saturated soil conditions negatively affect soil $CO_2$ efflux and optimum conditions likely vary with soil type and plant and microbial species.

Temperature is generally positively correlated with soil respiration (Lloyd and Taylor 1994). In a woody vegetation site in California, high rates of soil respiration were associated with higher soil moisture content and increasing soil temperatures while lower soil respiration rates were associated with late summer drought conditions and decreasing temperatures (Vargas and Allen 2008). However, the water status of soil also plays a role in the response of soil respiration to temperature. For example in a study in a Mediterranean climate, soil respiration was controlled by temperature when volumetric water content was higher than 10%, while during the dry summer soil water availability was the controlling factor (Almagro et al. 2009). Thus temperature and moisture can also affect soil organic matter decomposition and thereby affect soil respiration.

Root production is generally a function of seasonal plant carbon availability, but is also strongly affected by soil physical characteristics such as soil strength, soil water availability and soil temperature. The effect of soil water availability on root production and turnover is species dependent. For example, fine root biomass increased with an increase in precipitation in a Norway spruce stand (Gaul et al. 2008) while fine root productivity was not altered by irrigation of Scots pine with 50% less water, normal or 50% more water (Brunner et al. 2009). In a primary forest in East Malaysia, in randomly chosen 1 ha plots, soil water availability was positively correlated with root appearance rate but different branch orders and roots of different diameters were affected differently by soil water availability (Green et al. 2005). Older roots disappeared faster under high soil water availability while younger roots disappeared faster under low soil water availability (Green et al. 2005). Similarly, (Konopka et al. 2007) found that fine (< 1μm) roots were more susceptible to drought stress than slightly larger roots (1-2µm) and white root tips were more affected by drought stress than brown tips.  Thus, it appears that production and turnover of younger and finer roots is more negatively affected by drought stress than that of older, brown (likely lignified), roots. However, excessive water availability leads to anaerobic soil conditions which negatively affect root growth and production. Anaerobiosis generally leads to root mortality followed by greater emergence of adventitious roots in flood tolerant plants (Kozlowski and Pallardy 2002). Thus, both extremes of water availability (drought, flooding) negatively affect root production.

With seasonal variations in precipitation and potentially altered soil water availability under the different types of concrete, I expect to see seasonal and pavement induced variation in fine root production. With greater average soil water availability under pervious concrete, I expect that annual root production will be greater under pervious than under the impervious concrete.

## Significance and relevance of this study

In areas such as parking lots, paving cannot be entirely avoided and alternative solutions need to be considered. A useful alternative in this case could be the use of a permeable pavement system such as pervious porous concrete. Pervious pavements are ideally suited for light duty usage. The porosity of the pavement would facilitate infiltration of water (Bean et al. 2007a) and likely oxygen. Pervious porous pavement filters pollutants and may help to reduce runoff pollution (Scholz and Grabowlecki 2007). A greater infiltration of water and oxygen into the root zone can improve tree health when compared to a situation where only impervious pavement is used. A healthy root system will benefit overall tree health and canopy growth, thus adding shade and evaporative cooling benefits to urban areas.

New saplings take a minimum of 5 – 6 years to establish and the harsh urban conditions often lead to a high rate of mortality among saplings planted in large paved areas. Preserving already existing mature trees in paved areas would help to maintain the advantages that large trees provide over saplings such as more shade due to larger canopies, greater transpirational cooling and a larger already developed root system that can absorb water and nutrients and increase water infiltration capacity. In addition, established mature trees may be better able to survive the altered soil and air temperature conditions, provided adequate water and nutrients continue to reach the root system.

Pervious concrete has the least runoff from rainfall events and greater water infiltration compared to other pavement systems such as permeable interlocking concrete and pervious asphalt. With its better infiltration and oxygen diffusion, it is likely that pervious concrete provides a better soil environment for newly installed and existing mature trees.

My major objective is to test whether porous pervious concrete can be used as an alternative pavement to maintain mature trees in the landscape after development. This will be tested by examining soil respiration, soil chemistry and root growth of

*Liquidambar styraciflua* (American Sweetgum) trees under compacted soil, pervious and impervious concrete.

In my study, I compare the effects of three different pavement treatments, standard concrete pavement, porous pervious concrete pavement, and no pavement, on soil conditions, root growth of *Liquidambar styraciflua* (American Sweetgum) trees and soil $CO_2$ efflux. The hypothesis is that improved water and gas infiltration into the soil results in greater tree root growth and microbial activity under pervious pavements. With seasonal variations in precipitation and potentially altered soil water availability under different types of concrete, I expect to see seasonal and pavement induced variation in fine root production. With greater average soil water availability under pervious concrete, I expect that annual root production will be greater under pervious than under the impervious concrete.

In the next sections, Chapter I describes the effect of the different pavement treatments on soil $CO_2$ efflux, soil oxygen concentration, soil chemistry and root growth as affected by the pavement treatments. This chapter is followed by an overall discussion and an overall conclusion chapter.

# CHAPTER II

# EFFECT OF PERVIOUS AND IMPERVIOUS PAVEMENT TREATMENTS ON SOIL RESPIRATION, SOIL CHEMISTRY AND ROOT GROWTH OF AMERICAN SWEETGUM (*Liquidamabar styraciflua)*

## Introduction

Urban areas are characterized by higher temperatures and greater storm water runoff. Impervious surfaces are a significant cause of these problems (Rose and Peters 2001; Yuan and Bauer 2007). In this setting, trees can provide many environmental benefits. Trees reduce air temperatures by shading and transpirational cooling (Shashua-Bar et al. 2010) and also help remove air-borne pollution (Jim and Chen 2008) and can act as carbon sinks (Golubiewski 2006).

In the urban setting, it is a general practice to remove trees and compact the soil before pavement is laid. New trees are then planted in a pit within the paved area. The soil surrounding the newly planted trees is likely compacted and unsuitable for root growth. Water infiltration is likely reduced and oxygen diffusion slowed down due to both the imperviousness of the surrounding pavement and the high compaction levels of the surrounding soil. The newly planted trees consequently tend to be drought stressed, exhibit stunted growth, and appear unhealthy. Generally the canopy cover after development is only a fraction of the canopy cover that existed before development and this reduces the ecosystem services that urban trees can provide. Thus there is a need to preserve existing trees and canopy cover in urban areas, including areas where paving cannot be compromised.

Alternative pavement types may help alleviate some of the belowground stress of urban trees. Pervious concrete is an alternative concrete made up of the same materials as standard impervious concrete but where the fine aggregates are omitted such that pores are formed within the concrete (Tennis et al. 2004). This allows greater water infiltration than impervious concrete providing benefits in storm water runoff management (Collins et al. 2008) and likely provides better aeration to the soil beneath. The expected greater moisture infiltration and oxygen diffusion to the soil underneath pervious concrete compared to impervious concrete may provide a better root zone environment for growing trees compared to impervious concrete.

A good root zone environment is reflected by high root and microbial activity. Greater production and activity of roots and microbes lead to greater respiration rates which increase soil $CO_2$ concentration and subsequently the amount of $CO_2$ efflux from the soil to the surrounding air. Soil conditions such as soil moisture and soil temperature are known to strongly affect root and microbial respiration (Almagro et al. 2009; Lloyd and Taylor 1994; Nikolova et al. 2009). Extreme soil water contents at both ends (e.g., drought and flooding) generally decrease root and microbial respiration and thus soil $CO_2$ efflux (de Dato et al. 2009; Guntinas et al. 2009). Other soil characteristics such as the anaerobic soil conditions that are more prevalent in compacted soils also have a negative effect on root and microbial respiration (Czyz 2004; Stepniewski and Przywara 1992).

A good rhizospheric environment is also reflected by the amount of root production. Soil water content may be one of the factors affecting root production and turnover. Soil water content has variable effects on root turnover. Root production can increase with increasing soil water content (Gaul et al. 2008) or may not be affected by soil water content (Brunner et al. 2009).

The objective of my study is to determine whether pervious concrete can be used to preserve existing mature trees during urban development. If existing mature trees can stay healthy after pavement is placed over the root zone, I may be able to preserve the benefits that come from large trees (e.g., larger canopy area providing more transpirational cooling and shade) without compromising the need for paved areas. Therefore, the aim of this experiment is to measure the effect of three different pavement types on a range of soil environmental conditions (soil temperature, soil moisture, soil oxygen concentration, and soil nutrients) and to measure how these conditions affect root production and soil $CO_2$ efflux from the rhizosphere of pre-existing mature trees.

The three pavement treatments used were standard impervious concrete, pervious concrete and no concrete (control). I hypothesized that conditions of soil volumetric water content, soil oxygen concentration and temperature would vary under the three treatments such that moisture and aeration under pervious concrete would be greater than under impervious concrete and similar to the control treatment. I hypothesized that these changes would lead to greater root production and soil microbial activity under pervious pavement than impervious pavement and that root production and soil $CO_2$ efflux under pervious pavement would be very similar to the control plots.

## Materials and methods

### *Experimental setup*

My research site was located at the Texas A&M University Research Farm near the Brazos River in Burleson County, TX, USA (30° 33’ 11.80” N, 96° 25’ 37.49” W). The experimental setup has previously been described by Volder et al. (2009). In short, the trees used were 15 – 18 year old Sweetgum trees (*Liquidambar styraciflua)*, planted at least 5.8m from each other within rows and 8.0m between rows. The soil at the site was Ships clay soil with very slow permeability rates. Annual mean temperature of the area is 20.3°C (14.2°C minimum and 26.3°C maximum) and annual precipitation ranges between 762mm and 1016mm. During the experimental period, from February 2007 until August 2009, the site was not irrigated or fertilized, but was mowed 3-4 times during the growing season. Twenty-five trees were subjected to one of three pavement treatments – standard impervious concrete (5 trees), pervious porous concrete (10 trees) and no concrete or unpaved control (10 trees). During the experimental period one tree each of standard concrete, pervious concrete and control treatment died due to causes unrelated to the experiment (lightning, wind throw), thereafter the experiment was left with 4 standard concrete treatments, 9 pervious porous concrete treatments and 9 control treatments.

Concrete pads (3m x 3m x 8.5 cm deep) were poured over the root zones without any base material. Standard concrete was a mixture of Portland cement binder, 1cm aggregate and sand. Pervious porous concrete (Ecocreto, Austin, TX) was the same mixture with the sand omitted and a liquid polymer binder added to provide greater strength. Filter fabric was laid beneath both concrete treatments to prevent clogging of pore spaces in the soil. Six mil thick plastic barriers were placed inside 1m deep trenches along the edge of the plot to prevent any external moisture from entering into the root zones and to prevent roots from growing outside the soil space. This also simulated the urban conditions of restricted root growing space.

Of the 10 pervious concrete plots 5 plots were amended with EcoDirt (American Hydrosoil, Houston, TX). EcoDirt is a silicon-based material obtained from farm-grown products which are burned at high temperature into man-made sand which is 98% hollow. EcoDirt may aid in improving water holding capacity by absorbing water without expanding and later making it available. The ability to increase water holding capacity without expanding reduces soil expansion and shrinkage that may damage concrete pads, particularly in clay soils. EcoDirt was installed in a 30 x 30cm grid in 45 cm holes, 5 cm in diameter.

Six PVC collars (15 cm deep) were installed in each plot, two nearer the tree and four farther away in each corner (Fig. 1). Each collar was 12 cm wide and was covered with a PVC lid. Lids used on the pervious and the control plots were provided with four holes 1.5 cm wide each to allow gas exchange between the soil inside the collars and the atmosphere. The lids used on the concrete plots were not provided with holes to simulate the impervious concrete surface. On paved plots, the area immediately around the trunk

(30cm x 30cm) was not covered by concrete. The layout of the plots and the different measurements in each plot followed a pattern as shown in Fig. 1.

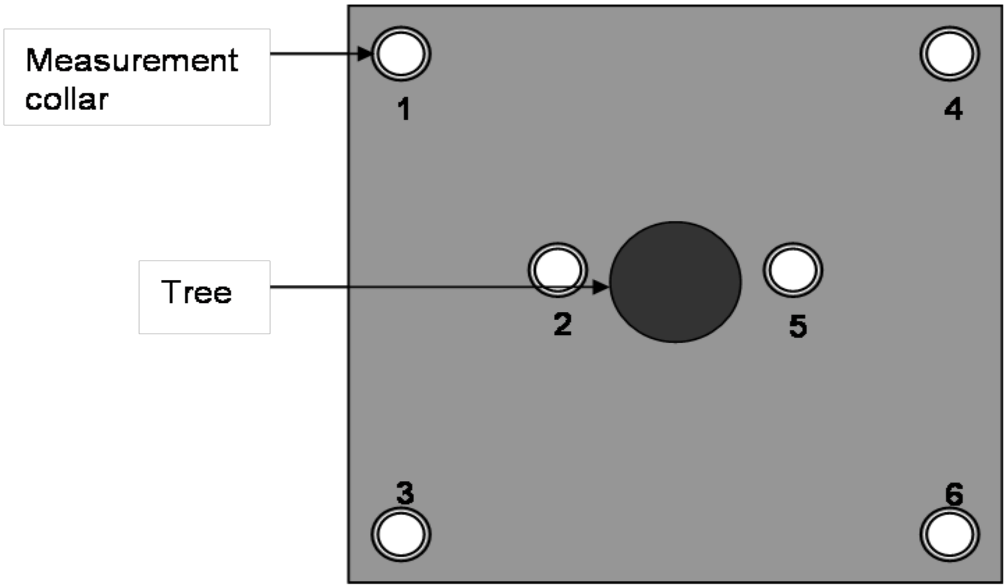


**Fig. 1** Positioning of collars for different measurements on control, standard and pervious concrete plots. Collars 2 and 6 were used for soil $CO_2$ efflux, soil volumetric water content and soil oxygen concentration, collar 5 was used for root growth, collar 3 was used for soil temperature

*Measurements*

Soil $CO_2$ efflux was measured monthly in each plot using the LiCOR 6400 (LiCOR Biosciences, Lincoln NE) with soil $CO_2$ efflux chamber attachment. Two collars, one close to the tree and one farther away from the tree were used for the measurements (Fig. 1). Three replicate measurements were made for each collar on each measurement date. For each measurement soil temperature at 5cm below the pavement was recorded as well. Measurements were made starting 10 am in winter months and 9 am in summer months and were alternated between both concrete treatments and control plots to avoid bias due to timing. Volumetric soil water content was measured using buriable time domain reflectometry (TDR) probes (MiniTrase, Soilmoisture Equipment Corp. Santa Barbara, CA). TDR probes were installed in the soil (0-20 cm) in the same collars that were used to measure soil $CO_2$ efflux measurements. Starting in July 2008, soil oxygen concentration measurements were taken monthly on the same days as the soil $CO_2$ efflux measurements. To measure soil oxygen concentration 2.5 cm wide and 15 cm long PVC tubes were inserted 5 cm deep below the base of the pavement, in the same collars that were used for soil $CO_2$ efflux measurements. For each measurement, the initial air present inside the tube was drawn out and released and a new air sample was drawn to get a fresh air sample for oxygen analysis. The gas collected was analyzed for oxygen content within 5 hours using an oxygen analyzer (Servomex 574, Servomex Co. Inc., Sugar Land, TX). To measure $CO_2$ and $O_2$ concentrations, gas samples collected (from the oxygen tubes) on August 13th 2009, were analyzed on a different analyzer.

Soil nutrients were quantified by cold water extracts of soil samples collected in the field (January 13th 2009 and February 25th 2009). Soil samples were collected at two points on each plot a) near the base of the trunk and b) side of the plot. The samples were obtained by digging and inserting a 2 cm diameter Sure-Shot auger at the 0-10 cm, 10-20 cm and 20-30 cm depths taking care to avoid soil underlying instruments.

Soil was air dried and sieved to 2 mm prior to addition of ultrapure water at a 1:10 soil:solution ratio in a 50 mL HDPE centrifuge tube. Each soil:solution unit was shaken for 1 hour and then centrifuged at 7,000 rpm (5856 g-force) under refrigeration. Samples were filtered using a 0.7 µm ashed (4 hrs at 500ºC) Whatman GF/F filter.

Dissolved organic carbon (DOC) and total dissolved nitrogen (TDN) were measured using high temperature Platinum-catalyzed combustion with a Shimadzu TOC-$V_{CSH}$ and Shimadzu total measuring unit TNM-1 (Shimadzu Corp. Houston, TX, USA). Dissolved organic carbon was measured as non-purgeable carbon using USEPA method 415.1 which entails acidifying the sample and sparging for 4 min with C-free air. Ammonium-N was analyzed using USEPA method 350.1 which is the phenate hypochlorite method with sodium nitroprusside enhancement (USEPA 1993a). Nitrate-N was analyzed using Cd-Cu reduction, USEPA method 353.3. Alkalinity was quantified using methyl orange (USEPA method 310.2; USEPA 1974) and was determined to be in the form of bicarbonate (Aq QA, Rockware Inc., Denver CO) for all samples. All colorimetric methods were performed with a Westco Scientific Smartchem Discrete Analyzer (Westco Scientific Instruments Inc. Brookfield, CT, USA). DON is the product of TDN – ($NH_3$-N + $NO_3$-N).

Further sub-samples of the air dried sample were used to quantify pH and conductivity. Briefly, 4g of soil was combined with 4 mL of deionized water and stirred. It was allowed to stand for 10 minutes. The suspension was swirled in the beaker and pH (Beckman 255 pH meter; Beckman Coulter Inc. Brea, CA), and electrical conductivity (EC) using an (Omega CGH-5021 EC meter; Omega Enginerring Inc. Stamford, CT) were recorded.

Sample replicates, blanks, NIST traceable and check standards were run every 12th sample to monitor instrument precision and co-efficient of variance among replicate samples which was set at a maximum of <4% CV or the sample was re-run.

Root images were collected biweekly using a minirhizotron setup (CI-600 digital root imager, CID Bio-Science Inc. Camas, WA). Transparent plastic tubes, 6.4cm wide and 103 cm long were installed, one per plot vertically in the soil inside the soil access holes (Fig. 1) with PVC caps placed over the access holes to prevent rainwater running down the tube. Images were captured at 4 successive depths at 0-20 cm, 20-40 cm, 40-60 cm, and 60-80 cm. Images were analyzed for total root length and alive root length using the root analysis program WinrhizoTron MF (Regent instruments Inc. Quebec, Canada)

The effect of soil temperature, soil volumetric water content and soil oxygen concentration on soil $CO_2$ efflux was analyzed using JMP statistical software (JMP 8.0, SAS, Cary, NC). The data was analyzed through ANOVA and post hoc student’s t for effect of treatment on $CO_2$ efflux, soil volumetric water content, soil temperature and soil oxygen concentration and through linear regression for effect of soil temperature, soil volumetric water content and soil oxygen concentration on soil $CO_2$ efflux and correlations between between soil volumetric water content and soil oxygen concentration. Treatment effects on root growth and soil chemistry parameters such as pH, EC, $NO_3$, TDN, $NH_3$-N, $PO_4$-P, DON, DOC and alkalinity chemistry were analyzed through ANOVA and post hoc student’s t.

Since the addition of EcoDirt within half of the pervious plots did not have a statistically significant effect on the variables measured, statistical analyses for pavement effects included all nine pervious pavement plots instead of five.

## Results

### *Soil $CO_2$ efflux*

For $CO_2$ efflux measurements there was no consistent effect of collar location on $CO_2$ flux (collar effect, $P = 0.807$, Table 1); however, for March 2008, December 2008 and February 2009, there was an effect of pavement treatment when grouped with collar location (pavement type x collar location x date effect, $P = 0.029$; Table 1). Since the collar effect was relatively small and inconsistent across dates, $CO_2$ fluxes were averaged across collars (Fig. 1). Efflux rates for both types of concrete plots ranged from 0 to 150 μmoles $CO_2$ $m^{-2}$ $s^{-1}$ (Fig. 2). This range of soil $CO_2$ efflux rates was much greater than normal expected rates (0 – 10 μmoles $m^{-2}$ $s^{-1}$) (Fang and Moncrieff 2001; Lloyd and Taylor 1994). On average, both concrete pavement types had greater efflux rates, 6.0 times (standard concrete) and 3 times (pervious concrete) that of control plots (pavement effect, $P < 0.001$, Table 1) and efflux rates on average from standard concrete plots were 1.8 times higher than pervious porous concrete plots, although this effect varied by date (pavement x date effect, $P < 0.001$, Table 1, Fig. 2)

**Table 1** Analysis of the effects of pavement type, collar location and measurement date on soil $CO_2$ efflux, soil temperature, volumetric water content and soil oxygen concentration. Different letters indicate significant differences between treatments at $P<0.05$ as determined with a Student's t-test

| | **Log($CO_2$)** | | **Soil Temperature** | | **Soil Moisture** | | **Soil Oxygen** | |
|---|---|---|---|---|---|---|---|---|
| | **F** | **P** | **F** | **P** | **F** | **P** | **F** | **P** |
| **Pavement type** | 31.28 | **<0.001** | 0.22 | 0.808 | 2.67 | 0.093 | 7.63 | **0.003** |
| **Date** | 35.85 | **<0.001** | 162.23 | **<0.001** | 142.29 | **<0.001** | 84.05 | **<0.001** |
| **Pavement*Date** | 4.23 | **<0.001** | 1.58 | **0.03** | 4.91 | **<0.001** | 4.83 | **<0.001** |
| **Collar location** | 0.06 | 0.807 | N/A | | 0.83 | 0.363 | 44.44 | **<0.001** |
| **Pavement*Collar** | 2.93 | 0.054 | N/A | | 22.83 | **<0.001** | 17.99 | **<0.001** |
| **Date*Collar** | 1.65 | 0.062 | N/A | | 1.16 | 0.298 | 5.43 | **<0.001** |
| **Pavement*Date*Collar** | 1.59 | **0.029** | N/A | | 0.71 | 0.88 | 2.75 | **<0.001** |

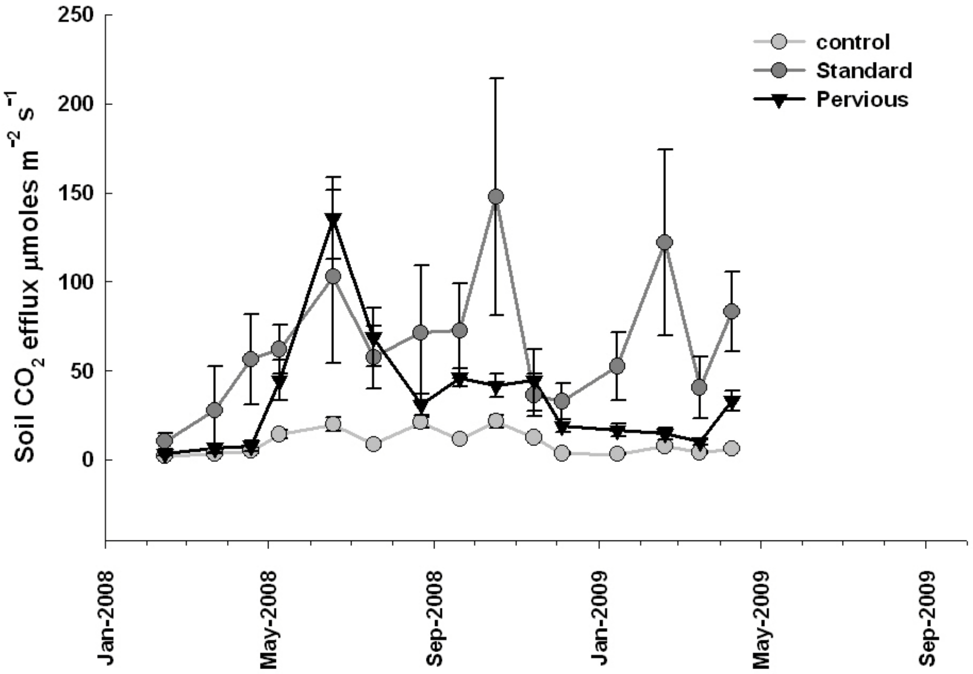


**Fig. 2** Mean soil $CO_2$ efflux in control, standard concrete and pervious concrete plots from February 2008 to September 2009. Bars indicate standard error

Soil $CO_2$ concentration, measured on August 13th, 2009, under the different pavement treatments showed that standard and pervious concrete treatments had greater soil $CO_2$ concentration than control plots ($P < 0.001$) while there was no difference between standard and pervious concrete plots (Fig. 3). Control plots had a mean soil $CO_2$ concentration of 0.28% while standard concrete and pervious concrete plots had mean soil $CO_2$ concentration of 0.70% and 0.66% respectively.

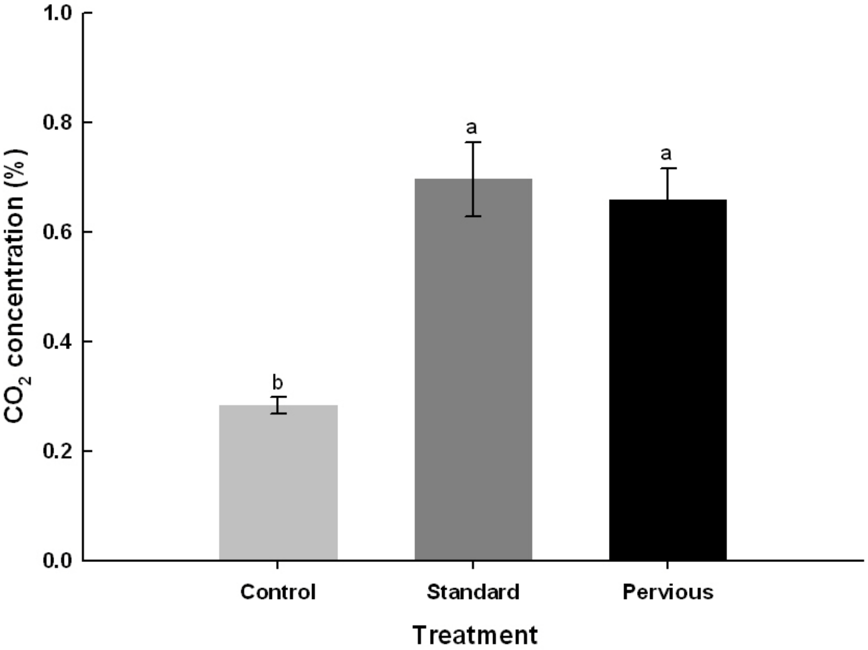


**Fig. 3** Mean soil $CO_2$ concentrations in control, standard concrete and pervious concrete plots on August 13th 2009. Bars indicate standard error (n=9 for control, n=4 for standard concrete, and n=9 for pervious concrete

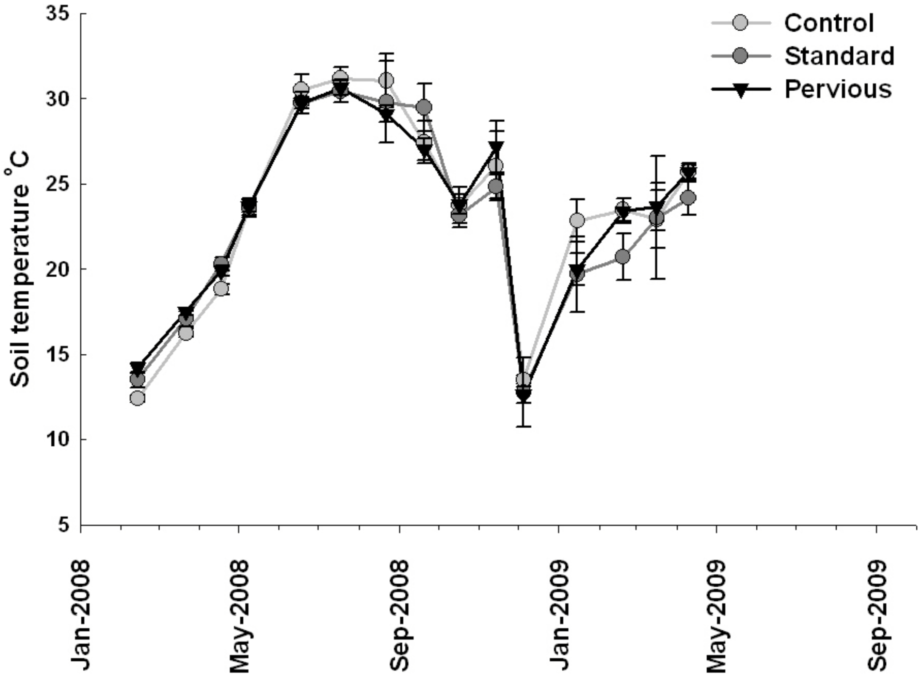


**Fig. 4** Mean soil temperature in control, standard concrete and pervious concrete plots from February 2008 to September 2009. Bars indicate standard error

### *Soil temperature*

Soil temperature itself was significantly affected by date (Fig. 4) but not affected by pavement treatment (Fig. 4). Soil temperature, overall did not affect soil $CO_2$ efflux but did affect soil $CO_2$ efflux within each treatment (Fig. 5). The effect was greater for pervious concrete plots ($P < 0.001$; $r^2 = 0.30$) than standard concrete ($P = 0.005$; $r^2 = 0.13$) and control plots ($P < 0.001$; $r^2 = 0.33$).

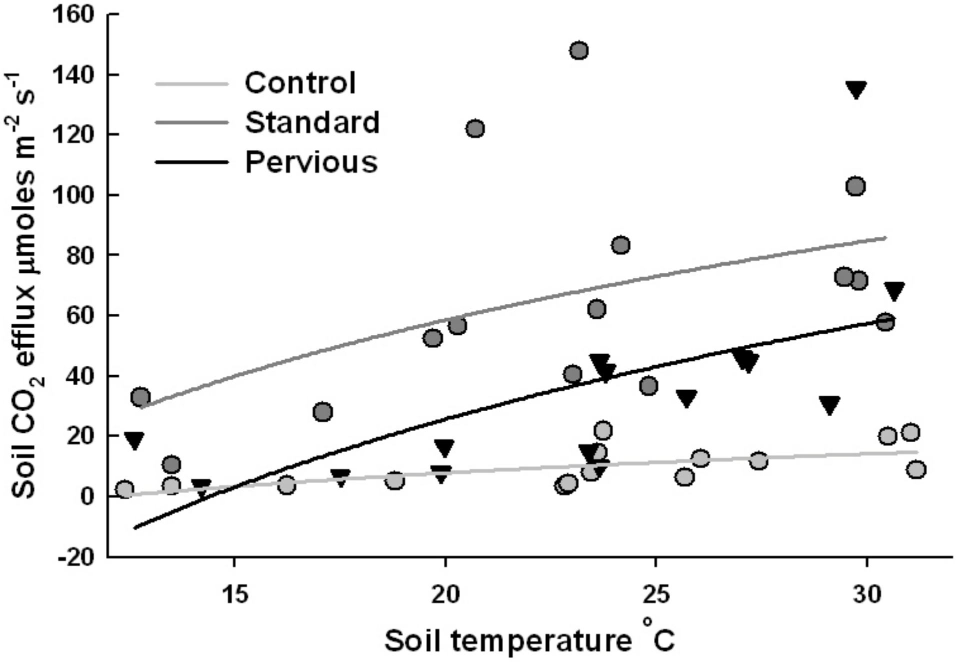


**Fig. 5** Effect of temperature on soil $CO_2$ efflux in control, standard concrete, pervious concrete plots for February 2008 to April 2009. Equations for the fitted curves are, for the control: Log ($CO_2$ efflux) = 0.16 + 0.076 * Temperature, $r^2 = 0.33$, $P < 0.001$; for the standard concrete: Log ($CO_2$ efflux) = 2.23 + 0.064 * Temperature, $r^2 = 0.13$, $P = 0.005$; and for the pervious concrete: Log ($CO_2$ efflux) = 0.34 + 0.11 * Temperature, $r^2 = 0.30$, $P < 0.001$. Only the intercept for the standard concrete treatment is statistically significantly different from 0 ($P = 0.005$)

**Table 2** Analysis of the full model of $CO_2$ efflux rates as affected by pavement type, soil water content, soil temperature, and date. Different letters indicate significant differences between treatments at P<0.05 as determined with a Student's t-test

| | **Log ($CO_2$ efflux)** | |
|---|---|---|
| | **F** | ***P*** |
| Pavement type | 40.58 | **<0.001** |
| Date | 11.48 | **<0.001** |
| Date x Pavement | 4.56 | **<0.001** |
| Temperature | 2.24 | 0.136 |
| Moisture | 0.11 | 0.737 |
| Oxygen | 0.88 | 0.348 |

### *Soil volumetric water content*

Averaged across time, the pavement treatment had an effect on moisture when grouped by date (*P*<0.001, Fig. 6, Table 1), soil under pervious concrete had greater water content than standard concrete treatments for the collar closest to the stem (*P*<0.001, Table 1), while there was no significant difference in soil water content between control and either of the other treatments. For the outer collar, that was located further from the stem (Fig. 1), there was no effect of pavement on soil water content (Fig. A-4). For both collar locations, the effect of the pavement treatment on volumetric soil water content varied with date (Table A-1, Fig. A-3). On average, there was no effect of soil water content on soil $CO_2$ efflux rates (Table 2, Fig. A-5).

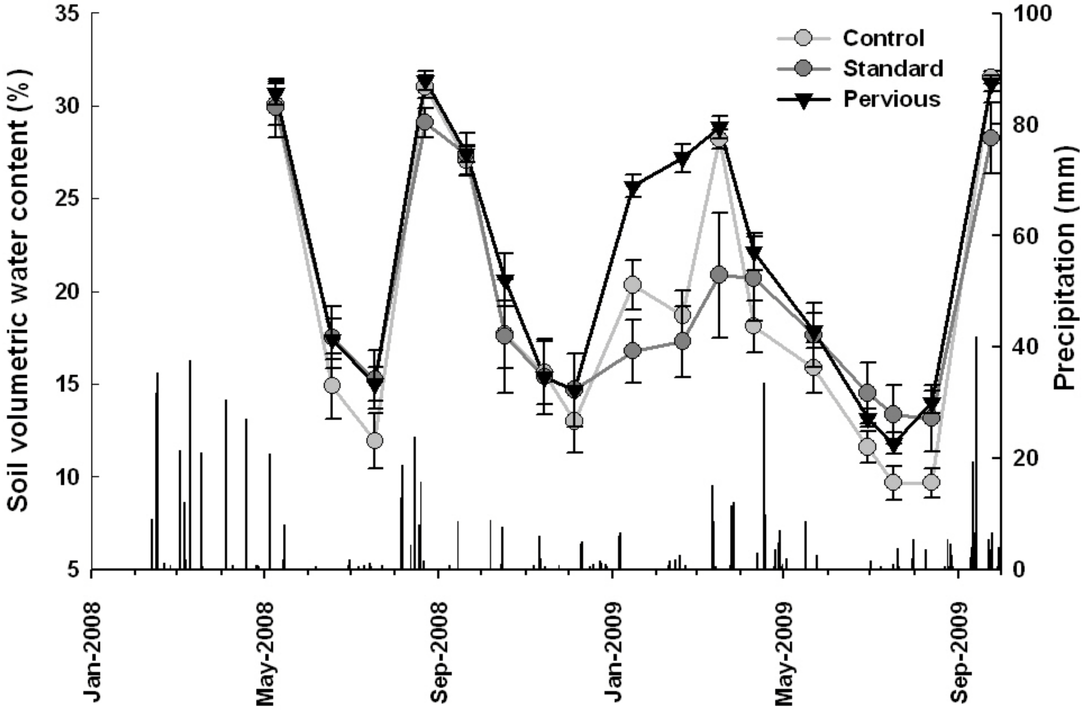


**Fig. 6** Mean soil water content in control, standard concrete and pervious concrete plots from February 2008 to September 2009. Bars on soil water contents indicate standard error. Bars (right axis) indicate precipitation values

### *Soil oxygen concentrations*

Averaged over both collars, soil oxygen concentration was lower under standard concrete than pervious and control treatments (*P* = 0.003; Table 1 Fig. 7). There was no difference in soil oxygen concentration between pervious and control treatments. Collar location also had an effect on soil oxygen concentration where samples from the outer collar had a greater soil oxygen concentration than samples from the collar closest to the stem (*P* < 0.001; Table 1). For the collar closest to the stem, standard concrete plots had lower soil oxygen concentrations (*P* < 0.001) than pervious concrete or control treatments and pervious concrete plots had lower soil oxygen concentrations than control treatments. For the outer collar, there was no difference between the pavement treatments. There was no overall relationship between soil oxygen concentration and soil $CO_2$ efflux rate (Table 2); however, there was a negative correlation between soil $CO_2$ efflux rates and oxygen concentration for the control plots only (*P* = 0.001; $r^2 = 0.17$; Fig. A-6).

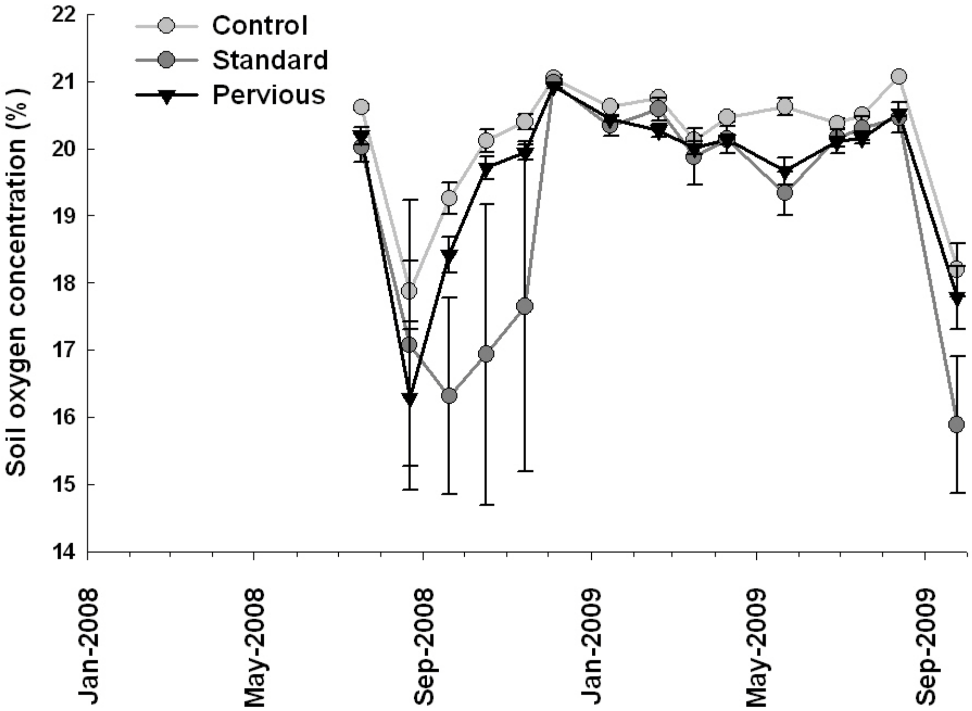


**Fig. 7** Mean soil oxygen concentration in control, standard concrete and pervious concrete plots from February 2008 to September 2009. Bars indicate standard error

A separate analysis of soil oxygen concentration using a different analyzer, performed on August 13 2009, showed that control plots had a greater soil oxygen concentration (*P* < 0.001) than standard concrete and pervious concrete plots (Fig. A-7). There was no significant difference in soil oxygen concentration between the two concrete treatments. Soil oxygen concentration decreased with increasing soil water content (Fig. 8). Beyond 23% soil water content, this effect was more pronounced for the standard concrete treatment than the control treatment and pervious concrete treatment.

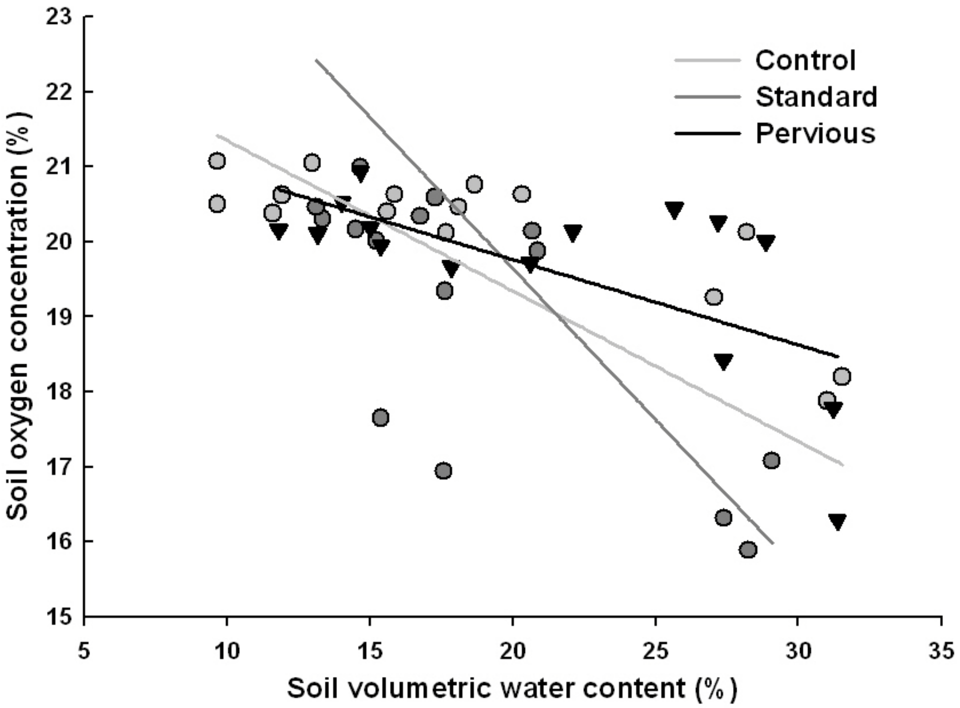


**Fig. 8** Effect of soil volumetric water content on soil oxygen concentration in control, standard concrete and pervious concrete plots for February 2008 to April 2009. Equations for the fitted curves are, for the control: Oxygen = 21.84 – 0.09 * Moisture, $r^2 = 0.48$, $P < 0.001$; for the standard concrete: Oxygen = 22.74 – 0.18 * Moisture, $r^2 = 0.29$, $P < 0.001$; and for the pervious concrete: Oxygen = 21.78 – 0.10 * Moisture, $r^2 = 0.32$, $P < 0.001$

### *Soil nutrients*

Samples were analyzed for effect of sampling location (side or trunk) on soil chemistry. pH, EC, $NO_3$-N, $NH_3$-N, TDN, DON, DOC, $PO_4$-P and alkalinity were analyzed for side and trunk samples at 0-10 cm, 10-20 cm, and 20-30 cm (Table A-2; Table A-3) and averaged for 0-20 cm depth (Table 3). Trunk samples had greater nitrate – nitrogen ($NO_3$-N) (Treatment x sampling location effect $P = 0.019$), total dissolved nitrogen (TDN) ($P < 0.001$), phosphate – phosphorus ($PO_4$-P) ($P < 0.001$), and dissolved organic nitrogen (DON) ($P < 0.001$) in standard and pervious concrete treatments than control. Soils had greater ammonia ($NH_3$) ($P < 0.001$) at the trunk for all three treatments and greater electrical conductivity (EC) for pervious concrete treatment ($P < 0.001$) than the other two treatments. Trunk samples also had a lower pH than side samples ($P < 0.001$) while there was no effect of sampling location on alkalinity.

With greater $NO_3$-N, TDN, DON and $PO_4$-P at the trunk than at the sides for both types of concrete treatments, difference in soil chemistry due to sampling location were likely due to stem flow and canopy runoff. Samples from the sides were considered more representative of differences due to the pavement treatments and therefore only the results of side samples are reported here. Overall, there were lower $NH_4^+$, TDN, DON and DOC concentration in the 10-20 cm soil layer compared to the 0-10 cm soil layer. However, there were no statistically significant differences due to pavement type nor were there any pavement type by soil depth interactions.

**Table 3** Mean values with corresponding standard errors and treatment effects on soil chemistry under control, standard and pervious concrete treatments at 0-20cm depth. Different letters indicate significant differences between treatments at $P<0.05$ as determined with a Student's t-test

| | **Control** | **Standard** | **Pervious** | **Significance** |
|---|---|---|---|---|
| **pH** | 8.17 ± 0.03 | 8.29 ± 0.02 | 8.30 ± 0.05 | 0.129 |
| **EC** | 254.71 ± 13.64 | 268.00 ± 24.32 | 233.75 ± 9.70 | 0.411 |
| **NO3** | 3.72 ± 0.48 | 6.69 ± 1.48 | 4.17 ± 0.94 | 0.218 |
| **NH3** | 1.15 ± 0.03 | 1.19 ± 0.05 | 1.24 ± 0.04 | 0.312 |
| **TDN** | 10.71 ± 0.94 | 11.71 ± 1.76 | 11.75 ± 1.49 | 0.954 |
| **DON** | 5.84 ± 0.66 | 3.83 ± 0.83 | 6.34 ± 0.91 | 0.210 |
| **DOC** | 96.54 ± 7.44 | 82.59 ± 10.68 | 106.09 ± 11.70 | 0.536 |
| **PO4-P** | 1.04 ± 0.21 | 0.99 ± 0.29 | 1.12 ± 0.35 | 0.956 |
| **Alkalinity** | 295.79 ± 46.60 | 362.75 ± 55.91 | 331.49 ± 25.04 | 0.532 |

### *Root growth*

Root data from under standard concrete, pervious concrete and control plots showed that control plots had greater standing alive root length than pervious concrete except in April 2009 and May 2009 ($P < 0.001$; Fig 9). Control treatments had a greater standing live root length than standard concrete treatments on most dates between July 2008 and Oct 2008 (Fig. 9) while standing live length in the standard concrete treatment did not differ between either treatment between October 2008 and March 2009 (Fig. 9).

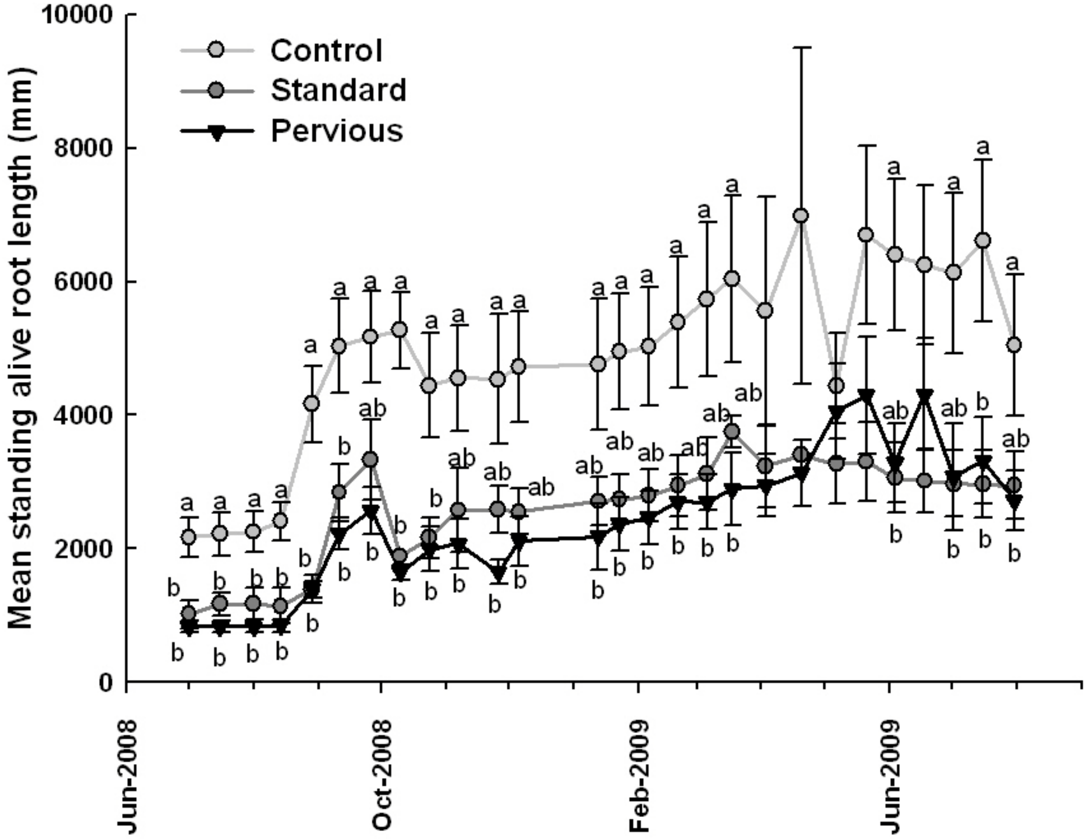
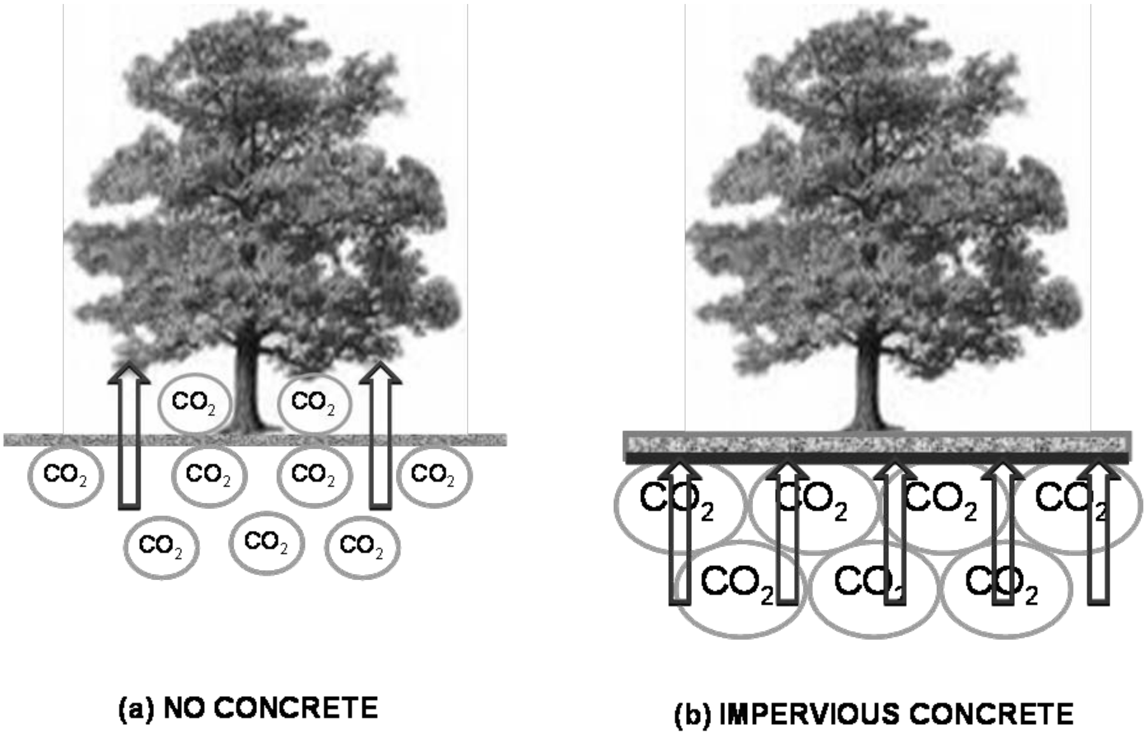


**Fig. 9** Mean standing alive root length from July 2008 to July 2009 under control, standard concrete and pervious concrete plots. Bars indicate standard error. Letters indicate significant effects. Different letters indicate significant differences between treatments at P<0.05 as determined with a Student's t-test

## Discussion

Soil $CO_2$ efflux normally falls in the range of 0-10 μmoles $m^{-2}$ $s^{-1}$ (Fang and Moncrieff 2001; Lloyd and Taylor 1994). Lloyd and Taylor (1994) studied the dependence of soil respiration on temperature and they used data that included respiration rates from Japan, UK, Germany and USA for their model, while Fang and

Moncrieff (2001) studied the dependence of soil respiration under laboratory conditions. Both experiments had rates of soil $CO_2$ efflux within the range of 0-10 μmoles $m^{-2}$ $s^{-1}$. In my study, however, soil $CO_2$ efflux rates for both concrete treatments were much higher than normal rates found in previous studies. Rates for standard concrete were 10-20 times normal rates while rates for pervious concrete were 5-10 times normal rates. The extremely high rates of soil $CO_2$ efflux from both concrete treatments and more so for the standard concrete treatment, is possibly because the concrete totally blocks air exchange between the soil and the atmosphere and prevents the natural efflux of $CO_2$ out of the root zone (Fig. 10). $CO_2$ concentration measurements showed values of 7000 ppm under standard concrete whereas the atmospheric $CO_2$ concentration is 385 ppm. This high gradient between the measurement collar and the atmosphere forces the accumulated $CO_2$ under the concrete to escape at a very high rate and my rates were therefore likely a measure of the concentration gradient between the soil and the atmosphere than actual soil respiration rates. This effect was more pronounced for standard concrete since it is totally impervious than pervious concrete that has more pore space that would allow some $CO_2$ to escape at all times. my initial aim was to look at differences in root activity below the different treatments. I did observe the expected seasonal pattern of lower $CO_2$ efflux rates in the winter, when roots and microbes are



(a) NO CONCRETE

(b) IMPERVIOUS CONCRETE

**Fig. 10** Model of how pavement increases soil $CO_2$ concentrations. (a) unpaved plot where soil $CO_2$ can escape at normal rates (b) impervious plot where soil $CO_2$ is accumulating under the pavement barrier

less active and thus the buildup of $CO_2$ is reduced, versus higher soil $CO_2$ efflux rates in the summer. However, it is unlikely that my rates were closely correlated to actual root and microbial activity and short-term responses were likely entirely masked by the large reservoir of soil $CO_2$ under the pavement treatments.

Previous studies have shown that high soil $CO_2$ affects root respiration rates. However, the high $CO_2$ concentration below my concrete pavements could be disadvantageous to root zones of trees depending on the species involved. For example, concentrations ranging from 130 ppm to 7015 ppm inhibited root respiration rates in Douglas Fir species (Qi et al. 1994), and also studies where soil $CO_2$ concentrations up to 2000 ppm did not affect root respiration of citrus or bean plants (Bouma et al. 1997) . However, in the Bouma et al. (1997) study, the concentration of $CO_2$ tested was only 2000 ppm and $CO_2$ concentration under the concrete in my experiment was 7000 ppm. Even though the Qi et al (1994) study examined $CO_2$ concentrations up to 7015 ppm, it is possible that high soil $CO_2$ responses are species specific and specific studies with high $CO_2$ concentration in sweetgum would have to be conducted to understand the root physiology even better.

Ships clay soil has a reportedly very low permeability rate, which could also be another factor involved in preventing easy escape of the accumulated $CO_2$ out of the soil (NCSS 1994). Studies have found that fine textured soils have greater $CO_2$ concentration than sandy soils since the smaller pore size do not allow easy escape of the respired $CO_2$ out of the soil (Bouma and Bryla 2000). Thus trees planted in concrete paved areas in the urban setting are likely experiencing very high levels of soil $CO_2$ concentration, especially when soils are highly compacted, and this may be one of the important reasons for poor performance of trees in paved areas apart from other reasons such as heat and drought stress.

Previous studies have shown that soil temperature under paved surfaces can be higher than unpaved surfaces (Celestian and Martin 2003; Montague and Kjelgren 2004). In the Celestian and Martin (2003) study, soil under asphalt parking lots, were found to be up to 40ºC. In studies by Montague and Kjelgren (2004) asphalt and concrete transferred more heat to the soil below than turf and consequently soil under these paved surfaces were warmer than turf and vegetative surfaces. I therefore expected that soil temperature under standard concrete would be higher than soil under control treatments. However I did not find any difference in soil temperature between the three treatments. This was also found by (Volder et al. 2009) using a different set of temperature probes that recorded hourly at the same experimental site. This could be likely due to the trees being mature with a large enough canopy that shaded most of the surface below which could have reduced the effect of incoming radiation. Therefore the difference in the surface, impervious, pervious with pores filled with air or no concrete did not make a difference. In the Montague and Kjelgren (2004) study, there was no canopy cover on the different surfaces while in the Celestian and Martin (2003) study, pavement and below ground temperatures were measured in an unshaded parking lot with a low albedo (black asphalt) surface. .

Soil $CO_2$ efflux is typically positively correlated with temperature (Lloyd and Taylor 1994; Peng et al. 2009; Rustad et al. 2001; Zhang et al. 2009). In this study, even though rates were abnormally high in the concrete treatments, an increase in soil temperature still increased soil and root respiration within each treatment. The rate of increase was greater for concrete treatments than control treatments (Fig. 5). Likely any increase in soil respiration may have caused greater buildup under the concrete and the greater concentration gradient could have led to greater efflux rates. Therefore, the effect f temperature could have been more due to greater $CO_2$ buildup than an actual temperature effect since temperature was not significantly different between the treatments. .

I expected the porosity of pervious concrete would lead to greater water infiltration into the soil and hence soil water content under pervious concrete would have greater soil water content than standard concrete. However, my results did not indicate that. Soil water content was overall unaffected by treatment in my experiment. This has also been reported by Volder et al. (2009) and Morgenroth and Buchan (2009). The Volder et al. (2009) study measured soil water content at the same experimental site but using a different set of soil moisture probes where the authors found soil water content in the 5-25 cm depth was not affected by treatment. This was surprising since laboratory tests of the pervious concrete blocks proved that they were 95% pervious. Therefore water from natural rain events was entering the pervious concrete but was not infiltrating the top soil. Possibly, the soil at this experimental site was the reason for this effect. The soils were Ships clay soil reported to have a very low permeability rate (NCSS 1994). It is possible that water that entered through the pervious concrete ran off the plot even before it could infiltrate into deeper soil layers because of the low permeability of the soils. This has also been discussed by Volder et al. (2009). The lack of an overall effect could also be due to the fact that my measurements were more sporadic (once every 4-6 weeks) and hence a direct treatment effect could have a biased result. More frequent measurements (hourly or daily) under the different treatments is likely to give a more accurate result.

Soil volumetric water content was, however, affected by pavement on some dates. In the spring of 2009, soils under the pervious concrete exhibited a greater volumetric water content than the control (Jan 2009 and Feb 2009) and standard concrete

(Jan 2009, Feb2009 and Mar 2009). In the spring, there was likely greater water input through pervious concrete plots than standard concrete and reduced evaporation from pervious concrete plots compared to the control treatment. In summer of 2009, both concrete plots had greater volumetric water content than the control. This was a drought period which extended from May 2009 to September 2009 (Fig. 6) and there was very little water input to the plots and it is likely that both concrete plots had reduced evaporative losses compared to the control plots since the concrete pavement was in place to prevent evaporation. The water that entered the soil under standard concrete was likely mostly through stem flow since the plots were non-pervious and hydraulically separated from the bulk soil by a 1m deep plastic barrier.

In order to understand soil water content differences between the two concrete pavement treatments with respect to control, I plotted a graph between soil water content values for control treatment versus both concrete treatments (Fig. 11). Fig 11 shows that up until 18% soil water content in the control plots, soil water content under both concrete plots was greater than or equal to that of control plots under these conditions. Likely, the concrete pavements reduced evaporation rates compared to control treatments and hence volumetric soil water content remained higher than in the control plots. Thus, during dry conditions, pervious and normal concrete would be more beneficial to roots of plants since they reduce evaporative losses. At higher soil water contents (> 20% volumetric soil water content in the control plots, likely within days of a rain event), soil water content in the pervious plots was equal to that in the control treatment, while standard concrete had soil water contents lower than in the control treatment. The pervious pavement allows as much water through as the control and thus mimics the hydrological behavior of the control plots while water does not penetrate easily into the plots covered with impervious pavement (other than through stemflow and possibly some capillary flow from the surrounding soil underneath the 1 m deep barrier). Thus after rain events pervious concrete maintains a higher soil water content than impervious pavement, while under drought conditions both pervious and normal concrete limit some water loss by reducing evaporative water losses from the soil.

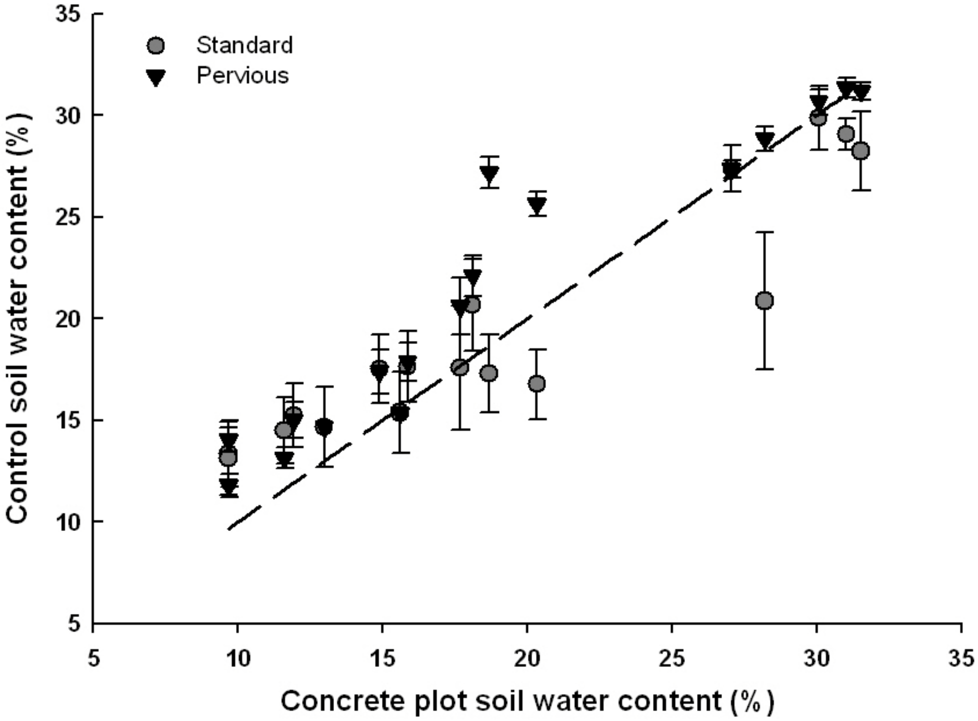


**Fig. 11** Soil volumetric water content in standard and pervious concrete plots in reference to control plots. The dashed line indicates the 1:1 line. Error bars indicate standard error

Soil $CO_2$ efflux is typically affected by soil water content (Davidson et al. 1998; Davidson et al. 2000; Nikolova et al. 2009; Reichstein et al. 2002). In my study, soil water content did not affect soil $CO_2$ efflux overall or within treatments. Any root and soil microbe respiratory responses to environmental conditions were likely buffered by the high $CO_2$ soil environment in the concrete treatments. Surprisingly however, soil water content did not affect soil $CO_2$ efflux rates in the unpaved plots either. In other studies soil $CO_2$ efflux rates were affected by extreme drought or flooding (Nikolova et al. 2009; Sowerby et al. 2008). In my study site, soil water content in the control plots was higher than 10% and soil oxygen concentration were higher than 17.5 % on all the measured dates, thus there were few measurement dates where drought was excessive or anaerobic conditions occurred. The lack of extreme soil water conditions was possibly the reason for a lack of a soil volumetric water content effect on soil $CO_2$ efflux rates.

The porosity of the pervious concrete also led to the assumption that oxygen infiltration would be greater under pervious concrete than standard concrete. My measurements confirmed this assumption. Soil oxygen concentration was lowest under standard concrete and greatest for control plots. Thus for trees growing under impervious paved areas, both high $CO_2$ as well as soil oxygen concentrations are issues that could be problematic.

For all three treatments, soil oxygen concentration was negatively correlated with soil volumetric water content as has been found in previous studies (Feng et al. 2002; Kallestad et al. 2008). However, when soil water content was greater than 23%, soil oxygen availability under the impervious concrete was lower than in the control or pervious plots. Thus, under wet conditions, for the same soil water content, soil oxygen availability was lower in standard concrete plots than in the other two treatments. At my site soil water content values greater than 23 % occurred in the impervious concrete plots on 3 out of the 17 measurement dates. Thus, anaerobic conditions are likely more prevalent under impervious surfaces than pervious surfaces, even when soils are at the same volumetric water content. This indicates that under wet conditions, the lack of oxygen diffusion through impervious surfaces will enhance anaerobic stress in impervious areas. The species in my experiment, sweetgum, is a wetland species and studies have shown that this species can survive with 15 cm flooding for one year (Angelov et al. 1996), and hence it is unlikely that my trees were strongly affected by the anaerobic soil conditions as indicated by a lack of effect of pavement on the diameter growth rate during the study period (Volder et al. 2009). However, non-wetland species growing in urban impervious paved areas may be more strongly affected by enhanced anaerobic conditions under impervious pavements during wet periods.

With the high soil $CO_2$ concentrations observed under the concrete, I expected that this would alter soil pH under the concrete and control treatments. High soil $CO_2$ would likely form carbonic acid under moist conditions and carbonic acid with a pH of 5.4 would make soil under concrete treatments more acidic. The input of organic leaf litter being negligible in both concrete treatments (other than through leaf litter accumulating around the trunk and the stem base), I expected that this might also affect soil carbon, nitrogen and phosphorus under the different treatments. Hence I proceeded to look at soil pH, EC, alkalinity, nitrogen, carbon and phosphorus under the different treatments. However, my results did not provide any conclusive differences in soil chemistry under the different treatments. There can be different possibilities for the lack of an effect on soil chemistry. a) the soil under the treatment was Ships clay soil, which is by nature moderately alkaline. It is possible that the soil had a buffering effect on the acidity of the soil. b) It is also possible that concrete which is lime based and by nature alkaline could have also had buffering effects on the soil.

Thus conditions under both concrete plots were high in $CO_2$ concentrations and standard concrete also had reduced aeration, especially at high soil water content. High $CO_2$ concentrations have been shown to affect soil respiration rates at concentrations greater than 300 ppm in an andosol soil from an upland field in Japan (Koizumi et al. 1991). High $CO_2$ concentrations increasing from 130 ppm to 7015 ppm were found to decrease root respiration rates exponentially in Douglas fir (Koizumi et al. 1991; Qi et al. 1994). The $CO_2$ concentrations encountered under the concrete plots were nearly 7000 ppm. These concentrations are generally found in field soils in summer (Kiefer and Amey 1992). Since these concentrations are likely to affect root respiration rates, root growth may also be inhibited. Possibly this was the reason why my root growth data showed greater mean alive standing root length for control plots than both concrete treatments. Since $CO_2$ concentrations were almost equally high in both concrete treatments, root growth was affected in both concrete treatments and there was no significant difference between the two pavement treatments.

## Conclusion

Under the standard and pervious concrete treatments, I found high rates of soil $CO_2$ efflux, high soil $CO_2$ concentrations and low soil oxygen concentrations especially at high soil water content levels. These adverse conditions under both the concrete treatments could have been the reason for an unfavorable root zone environment under both the concrete treatments and could have resulted in the reduced root growth that I found in comparison to control treatments in my experiment. Thus any barrier in the form of a pavement affects the root zone environment and could lead to altered root growth and root health that could eventually affect overall tree health as well. Surprisingly, however, there were no major differences between impervious and pervious concrete. There were no differences in soil temperature, soil volumetric water content or soil $CO_2$ concentrations between the two concrete treatments. Even though pervious concrete was more pervious it did not lead to greater soil volumetric water content levels. Possibly, the Ships clay soil with a low permeability rate resulted in low water infiltration rates and hence the water ran off the plots before it could infiltrate into deeper layers. Thus, possibly, soils play a very important role in the performance of pervious pavements. However, in another study, the use of sandy loam soils also did not provide conclusive differences in soil water content under the different concrete treatments (Morgenroth and Buchan 2009). This could be suggestive of the need for a base layer under the pervious concrete that is typically provided before construction. However, providing a base layer in this setting would lead to disruption of the root zone of the existing mature trees which would defeat the initial objective of my experiment of preserving mature trees to derive greater benefits from larger canopy and tree sizes.

Thus pervious concrete could be a good alternative, but not with heavy clay soils encountered at my experimental site. A possible solution would be to use pervious concrete on soils or media with high porosity and choosing trees that could have large canopies and yet survive in highly porous soil so that paved areas can benefit from the cooling from these trees and pervious concrete could still benefit the growth of these trees.

# CHAPTER III

# DISCUSSION

My objective of this study was to look at the performance of pervious concrete in terms of benefits to root zone environment of American sweetgum trees. I looked at soil respiration and root growth as a measurement of root zone health under impervious concrete, pervious concrete and no concrete (control).

Under impervious concrete, root zones are at a definite disadvantage because the concrete acts as a barrier that prevents gaseous exchange. Not only does impervious concrete prevent the infiltration of water and oxygen, but also prevents the escape of soil respired $CO_2$ into the atmosphere. My soil $CO_2$ concentration measurements showed phenomenally high levels under the impervious concrete. Soil oxygen concentration was also lowest under impervious concrete plots and hypoxia was more pronounced under impervious concrete than both the other treatments when soil water content was high. Thus, the soil and root zone environment under impervious concrete not only has very high $CO_2$ concentrations but also reduced oxygen content, even more so under wet conditions. Trees growing in impervious paved surfaces in urban areas are likely experiencing one or a combination of these stress factors apart from others like heat and drought stress and possibly add up to causing poor and stunted performance of these trees in the urban setting.

I expected that porosity of the pervious concrete would result in greater soil volumetric water content than under impervious concrete. Surprisingly, that was not the case even though laboratory tests conducted earlier had confirmed that the pervious concrete was porous. Hence it is possible that the soil under the concrete was responsible for the lack of a treatment effect on soil volumetric water content. The soil which was Ships clay soil has very slow permeability and it is likely that the water that infiltrated through the pervious concrete did not penetrate deeper layers and hence most of the water ran off the pervious plots. The lack of an effect on soil volumetric water content between the concrete and the control treatments could also have been due to this reason.

The lack of adequate water infiltration into deeper layers could also be a reason for the lack of a treatment effect on soil chemistry in terms of carbon, nitrogen and phosphorus which arise out of canopy runoff and stem flow. However, I expected that the high soil $CO_2$ would cause changes in acidity in the soil under the concrete treatments, but that was not the case. It is possible that either the soil at the experimental site has a high buffering capacity to neutralize the acidic pH, or the concrete itself (being lime based) adds to the alkalinity in the soil, or both.

The control treatments in my study significantly differed from both concrete pavements in having lower $CO_2$ concentrations and higher soil oxygen concentrations and likely the lower $CO_2$ coupled with greater oxygen concentrations led to greater root growth in the control than the concrete treatments. The control treatment therefore performed better than both the pavement treatments showing that a pavement barrier of either form was disadvantageous for root growth and the root zone environment.

# CHAPTER IV

# CONCLUSION

My initial objective to look at the suitability of pervious concrete for preserving existing mature trees during urban development still remains unanswered. The porosity of soil used under these pervious concrete systems has to be seriously considered. Soils that have a high permeability rate and which would allow easy water infiltration would be necessary to utilize the water infiltration benefits characteristic of pervious concrete. Not only for the infiltration of water, but also, the soils should allow greater escape of soil $CO_2$ out of the root zone and hence help to achieve more conducive environments for tree roots.

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# APPENDIX

**Table A-1** Analysis of the effects of pavement type, and date on soil volumetric water content in outer and inner collars. Effects are significant differences at P<0.05 as determined with a Student's t-test

| | VWC (inner collar) | | VWC (outer collar) | |
|---|---|---|---|---|
| | **F** | ***P*** | **F** | ***P*** |
| Pavement | 3.56 | **<0.001** | 0.56 | 0.582 |
| Date | 68.30 | **<0.001** | 67.37 | **<0.001** |
| Pavement x Date | 4.98 | **<0.001** | 3.02 | **<0.001** |

**Table A-2** Mean values of pH, EC, $NO_3$, $NH_3$, TDN, DON, DOC, $PO_4$-P and alkalinity with corresponding standard errors at 0-10 cm, 10-20 cm, and 20-30 cm in side samples of control, standard concrete and pervious concrete treatments

| | **0-10 cm** | | | **10-20 cm** | | | **20-30 cm** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Control** | **Standard** | **Pervious** | **Control** | **Standard** | **Pervious** | **Control** | **Standard** | **Pervious** |
| **pH** | 8.14±0.05 | 8.30±0.03 | 8.25±0.07 | 8.21±0.03 | 8.28±0.02 | 8.34±0.07 | 8.21±0.05 | 8.44±0.06 | 8.37±0.07 |
| **EC** | 281±23.71 | 267±36.18 | 232.5±15.67 | 231±10.86 | 269±36.76 | 235±12.32 | 226.25±16.58 | 166±18.06 | 234±22.37 |
| **NO3** | 3.83±0.58 | 7.69±2.42 | 3.82±0.58 | 3.62±0.77 | 5.69±1.87 | 4.53±1.83 | 3.31±0.61 | 4.00±1.50 | 3.29±0.58 |
| **NH3** | 1.18±0.06 | 1.30±0.05 | 1.32±0.06 | 1.12±0.04 | 1.09±0.03 | 1.15±0.04 | 1.04±0.03 | 1.14±0.08 | 1.21±0.09 |
| **TDN** | 12.10±1.50 | 14.23±2.86 | 13.25±1.97 | 9.46±1.07 | 9.20±1.63 | 10.24±2.24 | 9.56±1.25 | 7.41±1.28 | 8.98±1.11 |
| **DON** | 7.10±1.15 | 5.23±1.36 | 8.11±1.52 | 4.73±0.55 | 2.43±0.50 | 4.56±0.71 | 5.22±1.11 | 2.27±0.53 | 4.48±0.85 |
| **DOC** | 108.83±11.39 | 103.10±16.35 | 124.51±19.21 | 85.62±8.75 | 62.07±6.0 | 87.67±11.55 | 85.59±9.36 | 59.48±8.18 | 90.62±15.04 |
| **PO4** | 1.38±0.37 | 1.11±0.52 | 1.48±0.68 | 0.73±0.17 | 0.87±0.31 | 0.76±0.13 | 0.67±0.25 | 0.47±0.13 | 0.64±0.12 |
| **Alkalinity** | 221.16±27.78 | 328.53±28.39 | 313.26±24.61 | 362.13±80.21 | 396.96±112.59 | 349.72±44.35 | 271.25±40.26 | 334.28±40.31 | 332.44±14.42 |

**Table A-3** Mean values of pH, EC, $NO_3$, $NH_3$, TDN, DON, DOC, $PO_4$-P and alkalinity with corresponding standard errors at 0-10 cm, 10-20 cm, and 20-30 cm in trunk samples of control, standard concrete and pervious concrete treatments

| | **0-10 cm** | | | **10-20 cm** | | | **20-30 cm** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Control** | **Standard** | **Pervious** | **Control** | **Standard** | **Pervious** | **Control** | **Standard** | **Pervious** |
| **pH** | 7.93±0.10 | 7.95±0.01 | 8.03±0.06 | 8.13±0.03 | 7.96±0.02 | 7.99±0.07 | 7.97±0.04 | 8.27 | 8.29 |
| **EC** | 286.67±15.97 | 290±12.65 | 379±61.04 | 264.29±14.45 | 267.5±11.09 | 353.33±36.97 | 240±20 | 220 | 340 |
| **NO3** | 3.95±0.38 | 5.49±1.0 | 16.25±8.82 | 2.78±0.33 | 4.74±0.26 | 10.27±5.28 | 2.29±0.47 | 4.37 | 3.13 |
| **NH3** | 1.48±0.10 | 2.45±0.46 | 2.02±0.28 | 1.56±0.45 | 1.65±0.30 | 1.66±0.17 | 1.28±0.20 | 1.2 | 1.36 |
| **TDN** | 13.78±0.72 | 23.34±3.46 | 28.64±8.81 | 10.60±0.67 | 18.78±2.96 | 20.77±5.44 | 9.36±0.63 | 15.64 | 7.58 |
| **DON** | 8.35±0.64 | 15.41±3.12 | 10.36±1.51 | 6.27±0.68 | 12.39±2.76 | 8.83±1.17 | 5.79±0.04 | 10.07 | 3.09 |
| **DOC** | 134.79±8.01 | 192.07±28.68 | 159.81±14.26 | 119.10±7.58 | 190.92±38.57 | 157.59±19.35 | 122.34±18.07 | 155.17 | 65.2 |
| **PO4** | 2.24±0.50 | 6.16±1.77 | 4.05±1.04 | 0.90±0.19 | 2.81±1.12 | 2.58±0.90 | 0.79±0.09 | 0.81 | 0.78 |
| **Alkalinity** | 230.53±19.91 | 472.11±145.39 | 267.11±20.0 | 424.79±156.36 | 245.39±37.10 | 303.77±64.23 | 202.92±31.58 | 234.93 | 428.29 |

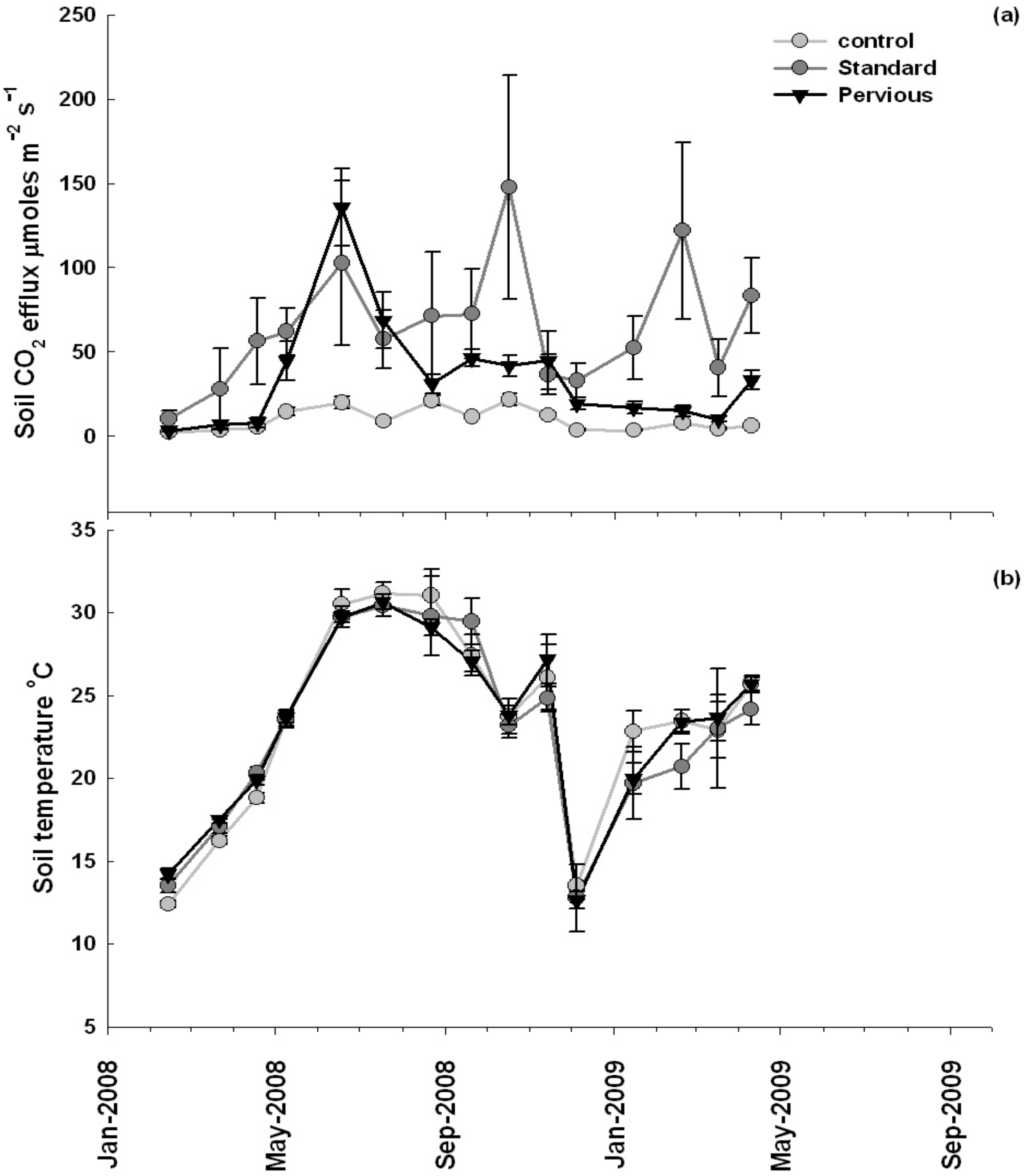

**Fig. A-1** Mean (a) soil $CO_2$ efflux and (b) soil temperature in control, standard concrete and pervious concrete plots from February 2008 to September 2009. Bars indicate standard error

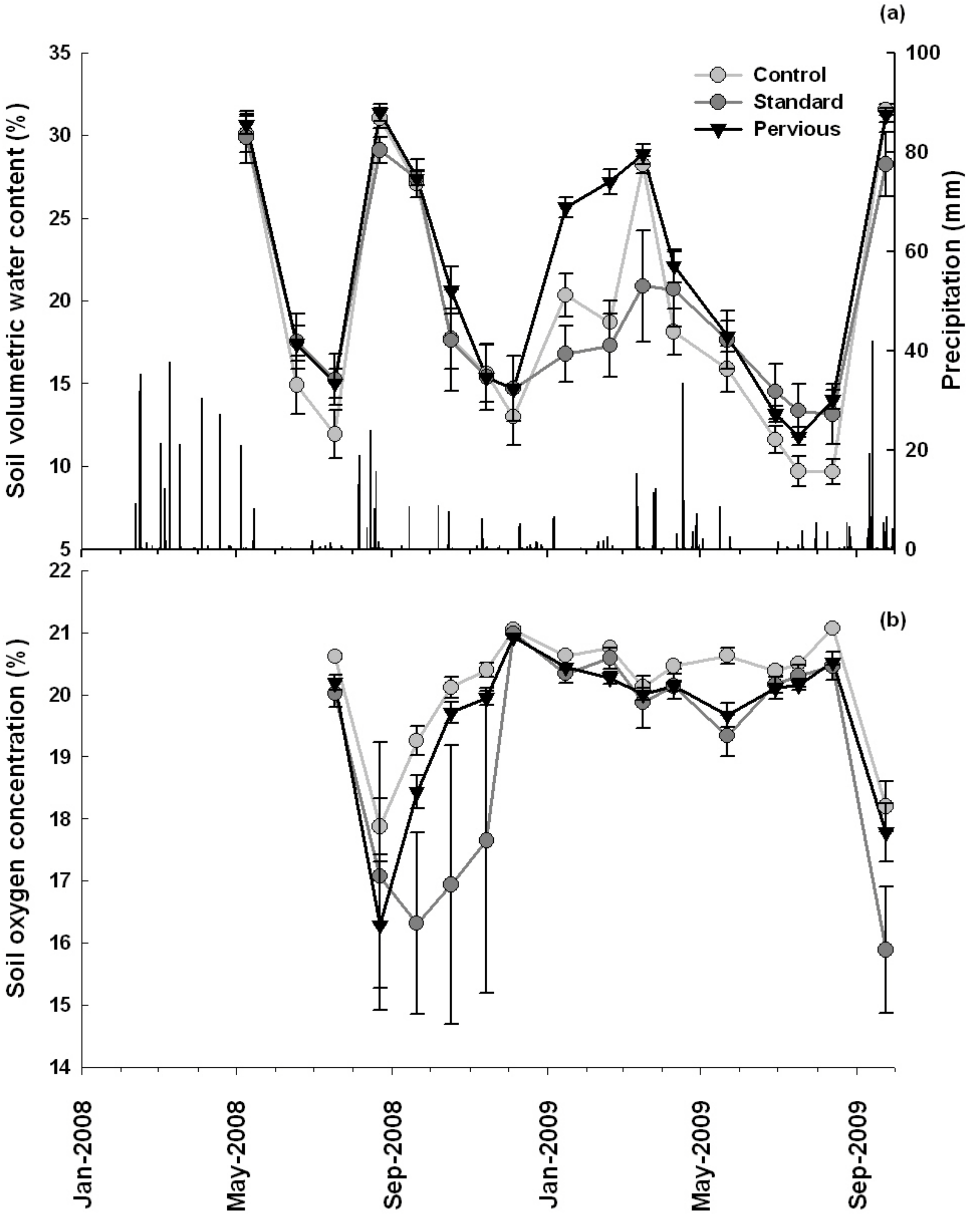

**Fig. A-2** Mean (a) soil water content and (b) soil oxygen concentration in control, standard concrete and pervious concrete plots from February 2008 to September 2009. Bars indicate standard error.

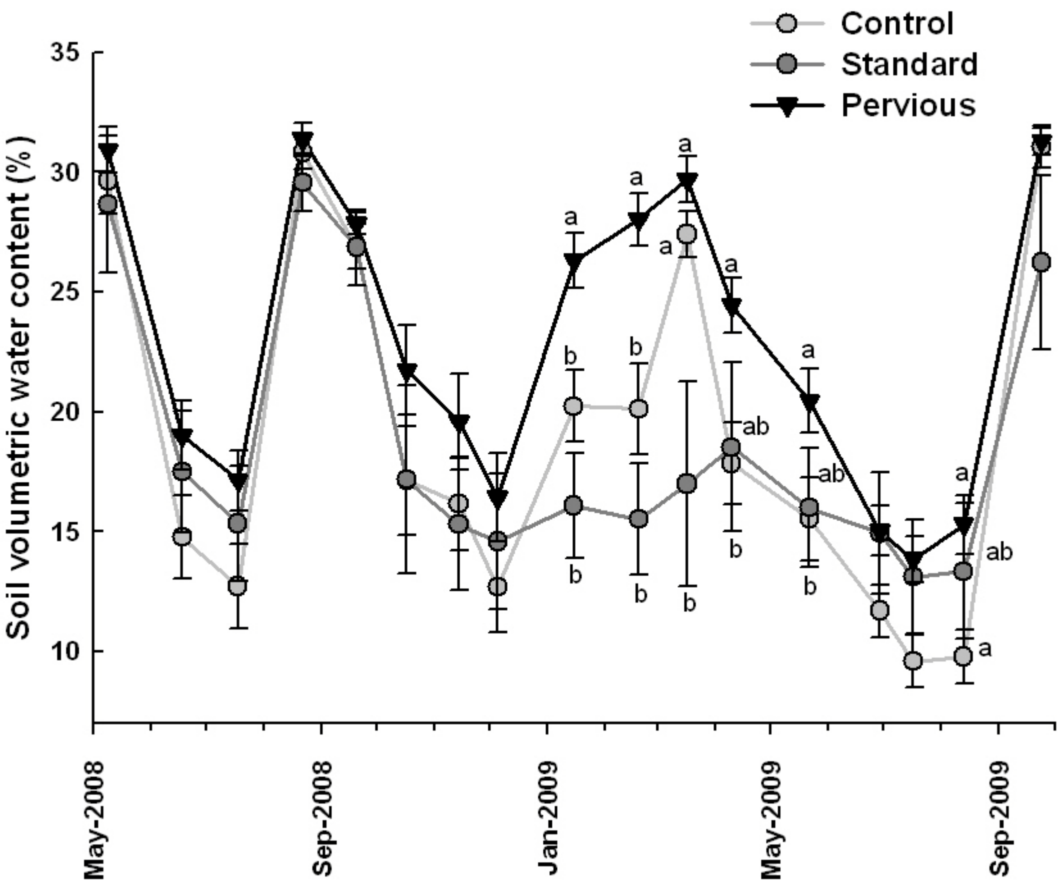

**Fig. A-3** Mean volumetric soil water content for inner collar in control, standard concrete and pervious concrete plots from February 2008 to July 2009. Bars indicate standard error. Different letters indicate significant differences between treatments at P<0.05 as determined with a Student's t-test

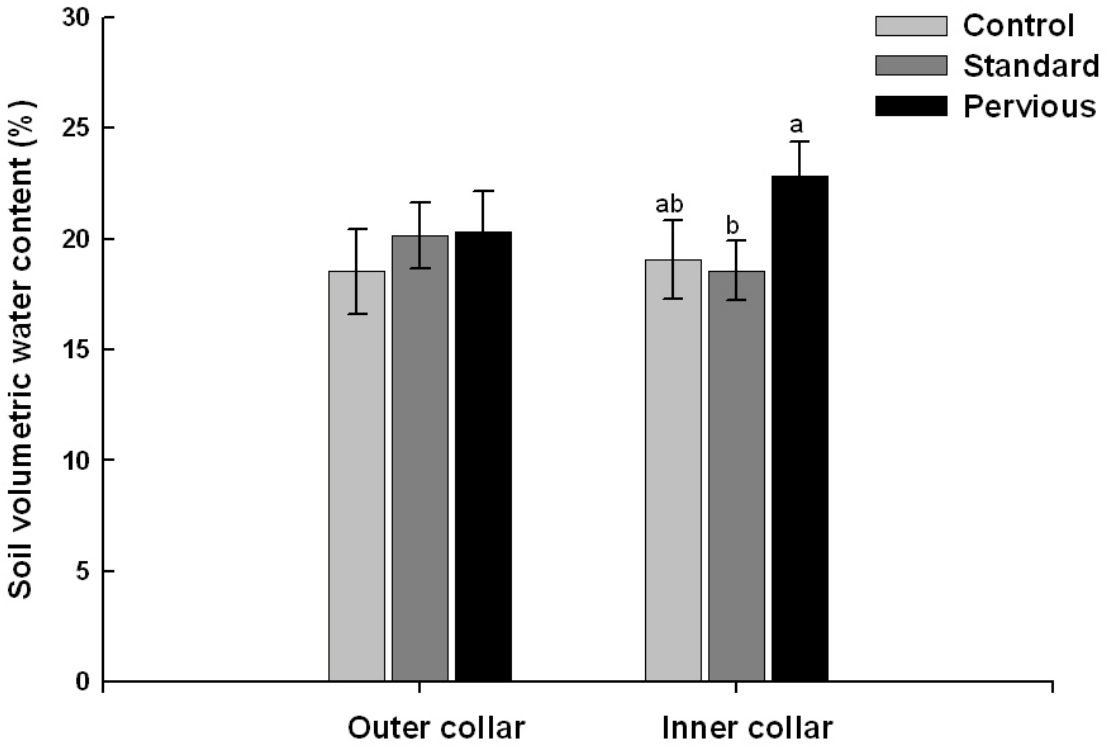

**Fig. A-4** Mean volumetric soil water content for outer collar and inner collar in control, standard concrete and pervious concrete plots from February 2008 to July 2009. Bars indicate standard error. Different letters indicate significant differences between treatments at $P<0.05$ as determined with a Student's t-test

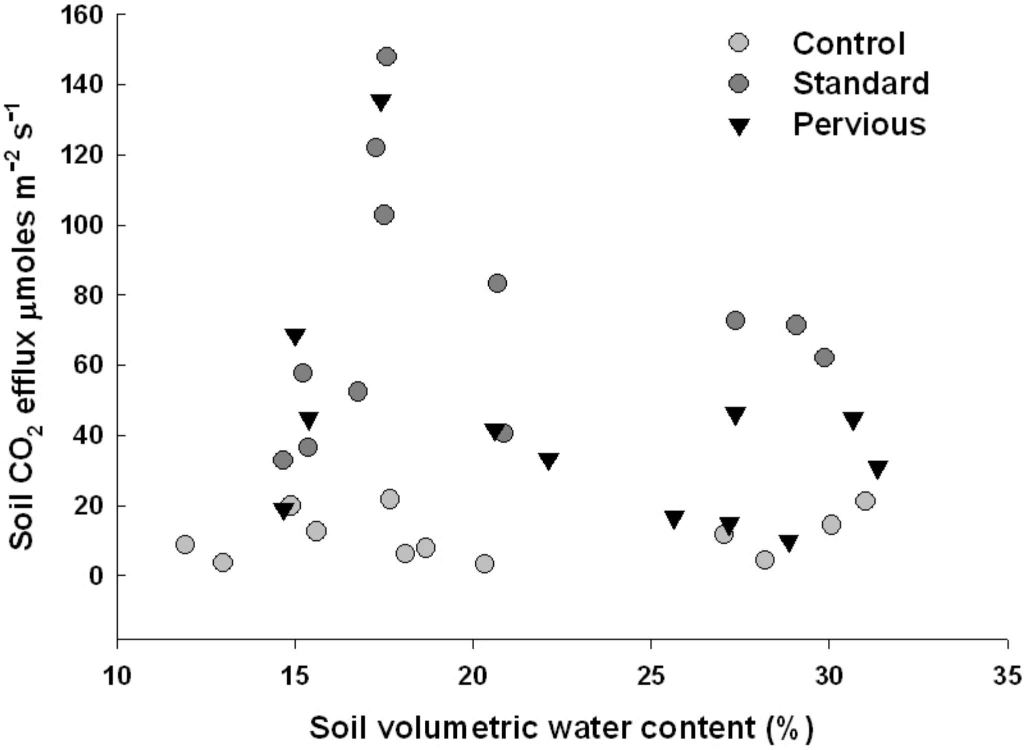

**Fig. A-5** Effect of volumetric soil water content on soil $CO_2$ efflux in control, standard concrete and pervious concrete plots for February 2008 to April 2009

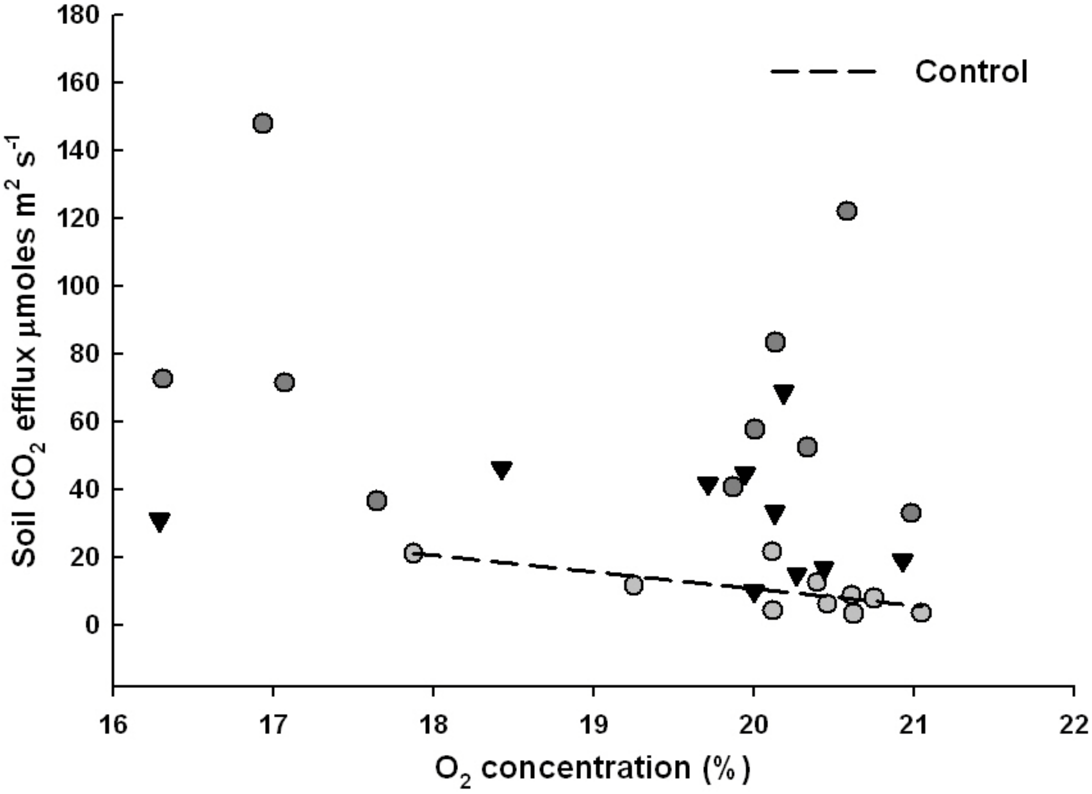

**Fig A-6** Effect of soil oxygen concentration on soil $CO_2$ efflux in control, standard concrete, pervious concrete plots for February 2008 to April 2009. Equations for the fitted line for the control: $CO_2$ efflux = 75.59 – 3.26 * Oxygen, $r^2 = 0.17$, $P < 0.001$

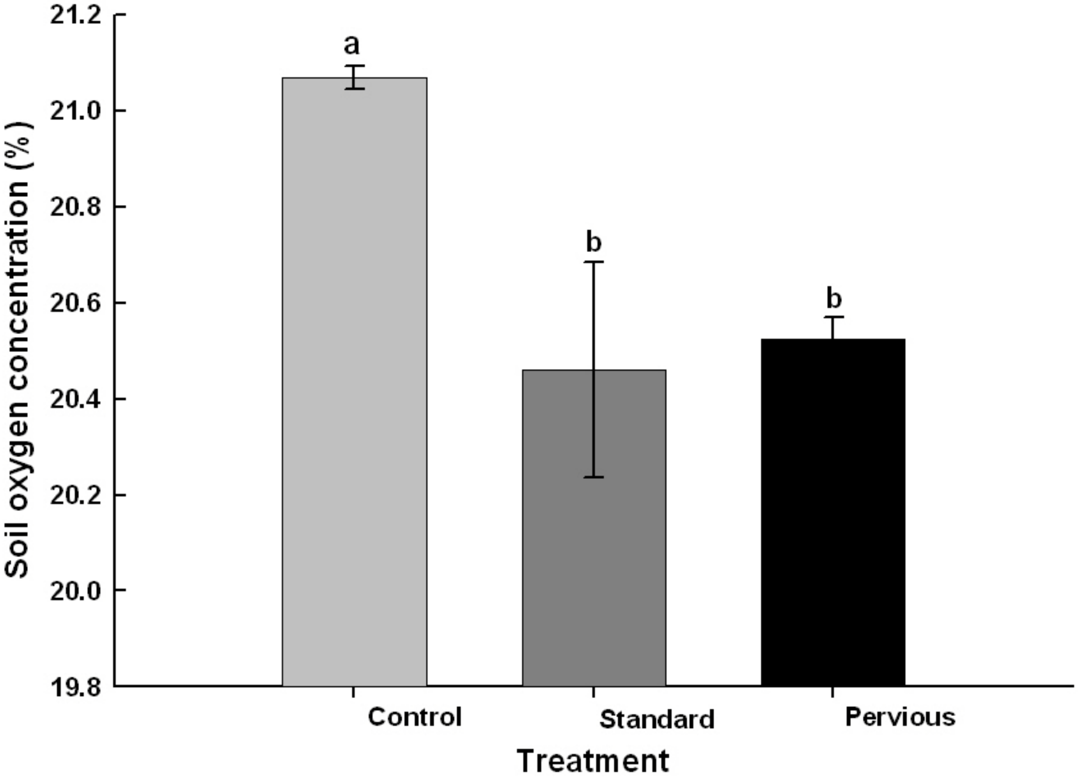

**Fig A-7** Mean soil oxygen concentration in control, standard concrete and pervious concrete plots on Aug 13th 2009. Bars indicate standard error

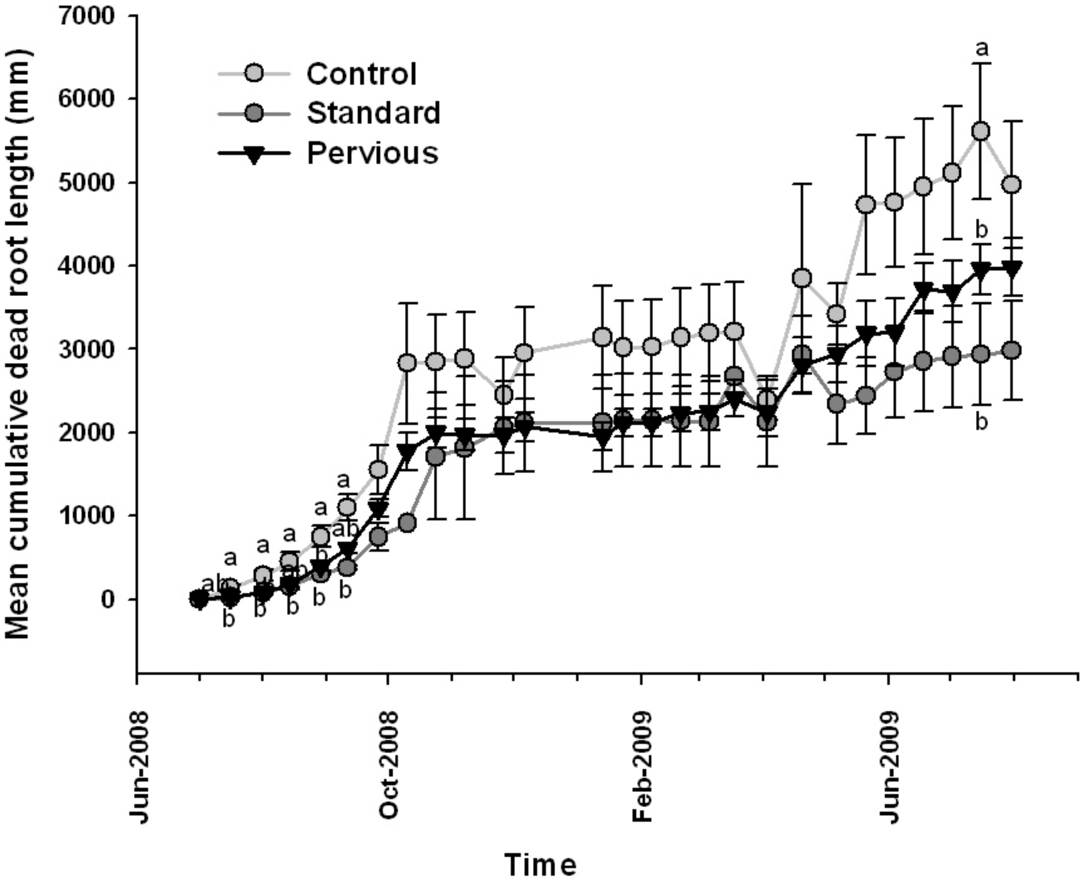

**Fig A-8** Mean cumulative dead root length from July 2008 to July 2009 under control, standard concrete and pervious concrete plots. Bars indicate standard error. Different letters indicate significant differences between treatments at P<0.05 as determined with a Student's t-test

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