# Effect of porous concrete on diameter growth and gas exchange of mature American sweetgum (Liquidamber styraciflua) trees

| | |
|---|---|
| Journal: | *Arboriculture & Urban Forestry* |
| Manuscript ID: | draft |
| Manuscript Type: | Original Article |
| Keywords: | American sweetgum, leaf fluorescence, leaf photosynthesis, Liquidamber styraciflua, parking lot, pavement, tree growth |

# Effect of porous concrete on diameter growth and gas exchange of mature American sweetgum *(Liquidamber styraciflua)* trees

Astrid Volder[1*], Todd Watson[2]

1 Department of Horticultural Sciences
Texas A&M University, TAMU 2133
College Station, TX 77843-2133
979 845 9277
a-volder@tamu.edu

2 Department of Ecosystem Science and Management
Texas A&M University, TAMU 2138
College Station, TX 77843-2138
979 458 1753
t-watson@tamu.edu

*Corresponding author

## ABSTRACT

Effects of three different pavement treatments: 1)no treatment; 2)impervious standard concrete; and, 3)porous concrete were compared over two years for their ability to modify growth and leaf gas exchange of American sweetgum *(Liquidamber styraciflua)* trees through their effects on soil moisture and soil temperature. Soil moisture and temperature dynamics of the porous plots were closely correlated with those in the control plots. Plots treated with standard concrete tended to have higher soil moisture content in the top soil layer and lower soil moisture content in deeper soil layers. Seasonal and overall tree diameter (dbh) relative growth rates were generally higher for the control trees and those treated with porous concrete compared to the growth rates of trees treated with standard concrete. Leaf gas exchange and fluorescence measurements were not affected by the treatments, and there was no effect of the treatments on leaf water potential.

Keywords: American sweetgum, leaf fluorescence, leaf photosynthesis, *Liquidamber styraciflua*, parking lot, pavement, tree growth

## INTRODUCTION

Numerous research studies have demonstrated that mature urban trees and urban forests provide many ecological benefits to urban areas. They reduce stormwater runoff , reduce air temperatures (Honjo and Takakura 1990; Avissar 1996), and remove pollutants (Beckett et al. 1998; Beckett et al. 2000). Unfortunately, urbanization has resulted in the loss of large numbers of mature forest trees on the rural-urban fringe. Urbanization in the South continues to grow at a rapid pace with most states experiencing double-digit (Chiesura 2004; Andersson 2006) population growth over the last 10 years. This growth is having a negative impact on watersheds throughout the region. Much of this negative impact is due to the increase in impervious surfaces and the subsequent loss of mature tree canopy along the rural-urban interface (Endreny 2004). Impervious pavements poured around mature trees generally result in a rapid decline of tree health and premature tree death. Impervious surfaces, such as parking lots, roads, and driveways, affect not only site hydrology, they affect plant physiology (Montague and Kjelgren 2004; Mueller and Day 2005; Ferrini and Baietto 2007), and they also contribute to urban heat islands that exacerbate air quality problems.

Permeable pavements have a high infiltration rate, from 130 mm per hour to up to several thousand mm per hour (Bean et al. 2007; Dietz 2007). This very high infiltration rate greatly reduces peak and total stormwater run-off rates, although the effectiveness strongly depends on the underlying soils. Porous concrete is most effective at reducing or completely eliminating runoff from small rainfall events. As the stormwater from a parking lot is filtered through the porous concrete and underlying soil, water quality can substantially improve (Legret et al. 1996; Barrett et al. 1998; Bean et al. 2007; Gobel et al. 2007), reducing the total phosphorus and nitrogen load by approximately 50% or more (Dreelin et al. 2006). Low available water, low oxygen, and high root zone temperatures under paved surfaces present a significant challenge to urban tree health and survival (Kozlowski 1999; Balakina et al. 2005). Porous concrete will allow for easier infiltration of both water and oxygen to the root zone, which we expect to greatly benefit root growth and production. In addition, the higher water content of the soil will reduce the radiative impacts of the concrete on the soil temperatures. Although several studies have focused on the performance of young or newly planted trees surrounded by different pavement types (Grabosky et al. 2001; Montague and Fox 2008), little is known about how existing, mature trees will fare when porous pavement is installed during development The expected higher water availability, higher root zone oxygen, and lower root zone temperatures are likely to greatly improve the health and growth of the trees compared to a situation where standard concrete would be installed. Experiments were established to test the hypothesis that 1) soils under the porous pavement will have higher summer soil moisture content than both the concrete and control treatment because of higher water infiltration and lower evaporation rates, 2) trees in the porous treatment would exhibit greater diameter growth than in the impervious treatment 3) trees in the porous treatment will have reduced summer water stress, as evidenced by less negative water potentials, higher photosynthetic rates, and higher fluorescence ratios than those in the impervious treatment.

## MATERIALS AND METHODS

In spring 2006, pavement research plots were established at the Texas A&M University Research Farm near the Brazos River in Burleson County, Texas (30º33'14.71"N, 36º25'33.61"W). Trees were growing in a Weswood silty clay loam soil. The site has an annual mean temperature of 20.3 ºC (68.5 ºF) ,14.2 ºC [57.5 ºF] minimum, and 26.3 ºC [79.3 ºF] maximum), and annual precipitation varies between 762 and 1016 mm (30 and 40 in). Root zones of twenty-five mature *Liquidambar styraciflua* (20 cm - 25 cm DBH (7.8 – 9.8 in), American sweetgum), were covered with four pavement combinations (standard concrete (5 trees), porous concrete (5 trees), porous concrete + water absorbing material (5 trees, Eco Dirt, Galveston, TX), and uncovered control (10 trees)). The plots (3m x 3m) were trenched to a depth of 90 cm (35.4 in) to remove roots that had grown outside of the pavement areas. A water and root impermeable barrier (6 mil thick plastic sheeting) was installed in the trenches around all plots to a 90 cm (35.4 in) depth to prevent root growth outside the experimental zone and lateral inflow of soil water into the experimental zone. This root barrier also simulated restricted root zones commonly found in most urban environments (Kopinga 1991). Concrete pads (9 cm (3.5 in) thick) were poured on top of uncompacted soil without any base material between the soil and the concrete. The porous concrete was donated by Ecocreto of Texas, and is basically a standard concrete mixture with the sand omitted that has been strengthened by a special additive (www.ecocreto.com). The resulting porous mixture is able to drain rainwater at a rate of 102 mm (4 in) per minute while strong enough to support 34.5 MN/m$^{-2}$ (5000 psi) in pressure. Filter fabric was installed beneath both types of concrete pads to prevent plugging of the pore spaces in the concrete with soil particles. Early in the experiment, one tree per pavement treatment died, leaving 4 trees in the standard concrete plots, 9 trees in the porous concrete plots, and 9 trees in the control plots. Due to concerns about the quality of the standard concrete, the standard concrete plots were sealed with a concrete resurfacer (Quikrete commercial grade concrete resurfacer) in February of 2007, thus only data collected after February of 2007 are reported in this paper.

The soil was a heavy clay soil with a high plasticity index and a high shrink/swell potential. Shrinking and swelling from this type of soil is known to cause cracks in pavement, thereby reducing the useful life of the pavement. Trees exacerbate this problem by rapidly reducing soil moisture through transpiration. Typically, shrink/swell is reduced by compacting soil to minimize pore space, but compacted soil asphyxiates tree roots. To determine if soil shrinking and swelling could be reduced without compaction, Eco Dirt, a burned silica material that absorbs water without swelling, was installed beneath five of the porous concrete plots. Holes (5 cm x 45 cm, 2 in x 18 in) were drilled vertically in the soil on a 30 cm (11.8 in) grid pattern within the test plots and filled with Eco Dirt. Trees were irrigated twice during the summer of 2006, but not thereafter. No fertilization was added and site maintenance included regular mowing around the plots.

Soil moisture and temperature sensors (2 each/plot, Decagon Devices) were installed at two depths (5 cm and 35 cm, 2 in and 13.8 in) under each slab in November 2005. Soil moisture and temperature data have been collected hourly since March 2007. Permanent dendrometers were installed on all tree trunks in March 2007 at 1.4 m (4.6 ft) to measure tree diameter growth, and data was collected bi-weekly. In addition, tree diameter was measured monthly at 1.4 m (4.6 ft) above grade using a diameter tape. Leaf gas exchange rates, water potential, and fluorescence characteristics were measured in June and September of 2007 and 2008, and light response curves of sun and shade leaves were collected in June 2007. Leaf gas exchange rates were measured on an external sun-exposed fully expanded leaf (1 per tree at each date). Light response curves were measured on two leaves per tree, one fully expanded leaf on the outside of the canopy (sun leaf, n= 1 per tree) and one fully expanded leaf on the inside of the canopy (shade leaf, n= 1 per tree). Leaf fluorescence characteristics were measured on dark leaves using dark clips (LiCor Biosciences, Lincoln, NE) that were placed on fully expanded external canopy leaves before sunrise on the measuring day (before 5.30 am), and on light adapted fluorescence characteristics were measured on fully expanded, sun exposed, leaves. All gas exchange characteristics were measured between 10.00 and 15.00. Pre-dawn water potential was measured on one fully extended external leaf (n=1 per tree), before sunrise. Gas exchange and fluorescence characteristics were measured using a LI-COR 6400 (LiCor Biosciences, Lincoln, NE) with controlled temperature and light intensity. Water potentials were measured using a pressure chamber (Soilmoisture Equipment Corp., Santa Barbara, CA). Tree diameters at 1.4 m (dbh) were measured using diameter tape on a monthly basis. Diameter relative growth rate (RGR) was calculated as $\ln(D_{t1})-\ln(D_{t0})/(t_1-t_0)$ (Hoffmann and Poorter 2002), where D = diameter (in mm) and $t_0$ and $t_1$ are the date of the initial measurement and the end date of the interval, respectively. The interval $(t_1-t_0)$ is expressed in days, and the resulting daily RGR is multiplied with 365 to calculate the annual RGR.

## Statistics

Data were analyzed using the Residual Maximum Likelyhood (REML) procedure, with pavement treatment and EcoDirt amendment as fixed factors using the statistical software JMP 7.0 (SAS institute). Within the porous concrete treatment, EcoDirt did not have a statistically significant effect on any physiological parameter, and treatment effects were subsequently analyzed using pavement treatment as the only fixed factor. This left 9 replicates for the porous pavement treatment, 4 replicates for the standard concrete treatment and 9 replicates for the control treatment. The REML procedure is very robust in its treatment of unequal replication.

## RESULTS

### Soil temperatures and water content

Soil moisture content varied seasonally (Figure 1) and soil moisture content was generally higher in the winter and spring months (October-May) than during the summer months (June-September). The pavement treatments did not have a very strong effect on seasonal moisture dynamics, although the soils under the standard concrete pavement treatment did appear to have consistently higher (~2% volumetric water content) volumetric water content during the summer in the upper soil layer (Figure 1A). In the deeper soil layers, the soils under the porous concrete generally had the highest volumetric water content, while the soils under the standard concrete tended to have the lowest volumetric soil water content. The addition of Eco Dirt made no difference to the moisture and temperature dynamics under the porous concrete and therefore all porous concrete results have been averaged together. The volumetric soil moisture dynamics before and after a spring rainfall event depended on soil depth and were strongly affected by the pavement treatments (Figure 2). In the upper soil layer, the volumetric soil moisture content increases were greatest in the control and porous concrete treatments. The volumetric water content increased from 18% to 32% in the control treatment, from 21.5% to 30% in the porous concrete treatment, and from 23% to 28% in the standard concrete treatment (Figure 2A). In the deeper soil layer, the plots with the standard concrete initially increased the most in volumetric water content (from 16% to 32%), however, within hours after the rainfall event, the high of 32% declined to 25.5%, whereas the control treatment and the porous concrete treatment stabilized at 31.4% and 28.9%, respectively (Figure 2B). Mean seasonal soil temperature was not strongly affected by the pavement treatments as expected. Surface soil temperatures tended to be marginally higher in the control plots during the spring and summer months when direct radiation inputs were high (Figure 3).

### Tree growth and physiology

Tree diameter relative growth rate during the summer of 2007 was higher in the porous and control plots than in the plots with standard concrete (Figure 4); however, in 2008 there were no statistical differences. There was no effect of Eco Dirt, so all the porous concrete treatments were averaged together. Net photosynthesis measurements in June 2007, September 2007, and June 2008 showed few differences between the treatments (Table 1). A lack of water stress may be responsible for the lack of treatment effects, since the pavement was expected to have the greatest effect on the trees through a potential reduction in summer water availability. Pre-dawn water potential measurements showed that the trees were not experiencing a significant amount of water stress early or late in both summers (Table 1). Lower Fv/Fm values in September are likely indicative of declining leaf quality due to senescence rather than any stress conditions.

Diameter relative growth rates varied by season (Figure 5) and were highest for trees growing in the porous concrete plots in the summer of 2007 and the spring of 2008. Over the whole experimental period, the diameter relative growth rates of the trees were highest in the porous concrete plots (Figure 4).

## DISCUSSION

We expected the porous concrete to provide the trees an advantage compared to standard concrete pavement by providing higher available soil water during summer conditions. We did not see any beneficial effect of porous concrete on volumetric soil water content during the summer months (Figure 1) nor did we see a noticeable effect on soil temperatures compared to control or standard concrete conditions. The lack of a temperature difference between the paved and unpaved plots partially contradicts a study on rhizosphere temperatures conducted by Celestian and Martin (2004) where they found that mean mid-day rhizosphere temperatures in a concrete parking lot were 15$^{o}$C higher than under a turfgrass surface. In our study, all temperature data were collected within a 2 m radius of the tree trunk, which meant that all plots were essentially shaded by the tree canopy for the majority of the day, thus there were few differences in radiation load between the plots. This lack of direct solar radiative input greatly reduced temperature differences between the plots in our study. Providing additional shade by keeping mature trees alive effectively maintained similar rhizosphere temperatures under paved and unpaved surfaces. During the spring and winter months, we did observe that soil water content was higher in the deeper soil layers in the porous concrete plots compared to the standard concrete plots (Figure 1). This is likely due to an enhanced flux of water down the profile after a rainfall event in the porous concrete plots compared to the standard concrete plots (Figure 2). Likely, the porous concrete acts as a temporary holding reservoir allowing water to infiltrate deeper into the soil, while excess water runs off the impermeable surface in the standard concrete treatment.

Why were soil water contents nearly identical during the summer months in both concrete treatments? Most likely, positive effects of the additional water influx due to the porosity of the concrete were negated by differences in canopy transpiration between the trees in the porous concrete and standard concrete plots. During the summer, when rainfall events become sporadic, average volumetric soil water content is mainly driven by water losses. At the end of the experiment, the trees in the porous treatments had the greatest dbh (220 ± 12.5 mm), followed by the control trees (213 ± 16.3 mm) and then the trees in the standard concrete (196 ± 19.4 mm). Since leaf physiological characteristics were not different between the treatments, the greater size of the porous trees, and presumed larger overall standing leaf area, likely translated into a greater transpiration rate by the trees growing in the porous treatment, thus explaining some of the lack of soil water content differences between the two concrete treatments during the summer.

As expected, soil temperatures were marginally higher in the shallow soil layers for the control plots. Warming the soil through heat transfer from the concrete was lower than the direct effect of solar radiation on the top soil. More surprisingly, there were no differences between both concrete treatments. We had expected that evaporation of water from the soil would be higher in the porous concrete plots and that soil under these plots would remain cooler than those under standard concrete plots. However, this was not the case (Figure 3).

Although there were large differences in mean rates of light saturated net photosynthesis in June 2007, there was no statistically significant effect of pavement treatment on leaf gas exchange (Table 1). Measured rates within each treatment were very variable. The ratio of variable fluorescence to maximal fluorescence is often used as an indication of stress, most commonly drought stress (Havaux 1992). Fv/Fm values in general were within the range of those reported for non-stressed plants , and the only significant treatment effect was found in July 2008, when Fv/Fm was lower for leaves of trees growing under standard concrete compared to porous concrete. However, even the rate in the standard concrete treatment (0.826) is generally considered representative of a healthy leaf (Maxwell and Johnson 2000). Based upon the pre-dawn water potentials measured in this experiment, trees were not experiencing very stressful conditions in terms of water availability. This is confirmed by the soil water content data, where seasonal water content over the summers of 2007 and 2008 averaged around 15%.

In terms of growth rates, the trees in the porous plots had a 68 % greater diameter relative growth rate over the whole experiment than those in the concrete plots. Thus, in spite of a lack of treatment effects on soil water content, soil temperature and leaf physiology, trees in the porous concrete plots outperformed those in the other two treatments. This effect was particularly strong in the 2007 spring and summer, and the 2008 spring season.

## CONCLUSION

Porous concrete could be a good alternative to use around existing mature trees. In this study, the use of porous concrete does not significantly affect the soil water and temperature conditions around mature trees in the summer, but may enhance spring growth conditions. Mean tree diameter relative growth rate was 68 % greater for trees growing in the porous concrete plots compared to those growing in the standard concrete plots and thus porous concrete, depending on installation techniques, can be used as an alternative pavement to enhance growth and survival of mature trees during development.

## ACKNOWLEDGEMENTS

This project was partially funded by the USDA Forest Service and the Texas Forest Service. Concrete material and labor for plot installation were donated by EcoCreto of Texas, Inc. and Mr. Jaime Grau. Eco Dirt was donated by Aabaco Industries Inc. David Dickson, Isaiah Morgan, Dudley Bernard, Russell Book, Bhavana Viswanathan and Thomas Martinez-Trinidad provided field support for this project.

## LITERATURE CITED

Andersson, E. (2006). Urban landscapes and sustainable cities. Ecology and Society 11: 34.

Avissar, R. (1996). Potential effects of vegetation on the urban thermal environment. Atmospheric Environment 30: 437-448.

Balakina, J.N., E.J. Ros, A.J. Koolen, W.K.P.v. Loon, O.V. Makarova, V.V. Bondarenko and L.J. Koudstaal (2005). Simulation of oxygen regime of tree substrates. Urban forestry & urban greening 4: 23-35.

Barrett, M.E., P.M. Walsh, J.F. Malina and R.J. Charbeneau (1998). Performance of vegetative controls for treating highway runoff. Journal of Environmental Engineering-Asce 124: 1121-1128.

Bean, E.Z., W.F. Hunt and D.A. Bidelspach (2007). Field survey of permeable pavement surface infiltration rates. Journal of Irrigation and Drainage Engineering 133: 249-255.

Beckett, K.P., P.H. Freer-Smith and G. Taylor (1998). Urban woodlands: their role in reducing the effects of particulate pollution. Environmental Pollution 99: 347-360.

--- (2000). The capture of particulate pollution by trees at five contrasting urban sites. Arboricultural journal 24: 209-230.

Celestian, S.B. and C.A. Martin (2004). Rhizosphere, surface, and air temperature patterns at parking lots in Phoenix, Arizona, U.S. Journal of arboriculture 30: 245-252.

Chiesura, A. (2004). The role of urban parks for the sustainable city. Landscape and Urban Planning 68: 129-138.

Dietz, M.E. (2007). Low impact development practices: A review of current research and recommendations for future directions. Water Air and Soil Pollution 186: 351-363.

Dreelin, E.A., L. Fowler and C.R. Carroll (2006). A test of porous pavement effectiveness on clay soils during natural storm events. Water Research 40: 799-805.

Endreny, T.A. (2004). Storm water management for society and nature via service learning, ecological engineering and ecohydrology. International Journal of Water Resources Development 20: 445-462.

Ferrini, F. and M. Baietto (2007). Effect of compost-amended backfill and paved surface on leaf parameters and physiology of Norway maple (*Acer platanoides* L.). Arboriculture & Urban Forestry. Champaign, USA, International Society of Arboriculture: 33 6, 386-391.

Gobel, P., C. Dierkes, H. Kories, J. Messer, E. Meissner and W.G. Coldewey (2007). Impacts of green roofs and rain water use on the water balance and groundwater levels in urban areas. Grundwasser 12: 189-200.

Grabosky, J., N. Bassuk, L. Irwin and H.v. Es (2001). Shoot and root growth of three tree species in sidewalks. Journal of Environmental Horticulture. Washington, Horticultural Research Institute: 19 4, 206-211.

Havaux, M. (1992). Stress tolerance of photosystem-II in vivo - antagonistic effects of water, heat, and photoinhibition stresses. Plant Physiology 100: 424-432.

Hoffmann, W.A. and H. Poorter (2002). Avoiding bias in calculations of relative growth rate. Annals of Botany 90: 37-42.

Honjo, T. and T. Takakura (1990). Simulation of thermal effects of urban green areas on their surrounding areas. Energy and Buildings 15: 443-446.

Kopinga, J. (1991). The effects of restricted volumes of soil on the growth and development of street trees. Journal of arboriculture 17: 57-63.

Kozlowski, T.T. (1999). Soil compaction and growth of woody plants. Scandinavian Journal of Forest Research 14: 596-619.

Legret, M., V. Colandini and C.l. Marc (1996). Effects of a porous pavement with reservoir structure on the quality of runoff water and soil. Science of the Total Environment: 189-190.

Maxwell, K. and G.N. Johnson (2000). Chlorophyll fluorescence - a practical guide. Journal of Experimental Botany 51: 659-668.

Montague, T. and L. Fox (2008). Gas exchange and growth of transplanted and nontransplanted field-grown Shumard red oak trees grown with and without organic mulch. Hortscience 43: 770-775.

Montague, T. and R. Kjelgren (2004). Energy balance of six common landscape surfaces and the influence of surface properties on gas exchange of four containerized tree species. Scientia Horticulturae 100: 229-249.

Mueller, E.C. and T.A. Day (2005). The effect of urban ground cover on microclimate, growth and leaf gas exchange of oleander in Phoenix, Arizona. International Journal of Biometeorology 49: 244-255.

1

**Table 1**. Light saturated net photosynthesis (*A*), variable to maximum fluorescence ratio ($F_v/F_m$), and pre-dawn water potential ($\Psi_{PD}$ ) as measured on leaves of American sweetgum exposed to different concrete treatments. Leaves were selected from the outside of the canopy where they were exposed to full sun. Values are ± se, different letters behind means indicate statistically significant differences at $P < 0.05$.

| Date | Pavement Type | *A* (µmol $CO_2$ $m^{-2}$ $s^{-1}$) | $F_v/F_m$ | $\Psi_{PD}$ (MPa) |
|---|---|---|---|---|
| **June 19, 2007** | Control | 15.05 ± 2.38 | 0.829 ± 0.0091 | -0.18 ± 0.018 |
| | Porous | 9.98 ± 2.72 | 0.817 ± 0.0053 | -0.24 ± 0.033 |
| | Standard | 12.94 ± 1.34 | 0.832 ± 0.0018 | -0.19 ± 0.046 |
| **Sep 21, 2007** | Control | 7.37 ± 1.43 | 0.804 ± 0.0077 | -0.35 ± 0.023 |
| | Porous | 8.84 ± 1.25 | 0.809 ± 0.0080 | -0.41 ± 0.029 |
| | Standard | 9.64 ± 0.49 | 0.806 ± 0.0167 | -0.40 ± 0.046 |
| **July 1, 2008** | Control | 4.18 ± 0.77 | 0.831 ± 0.0021 ab | -0.26 ± 0.090 |
| | Porous | 3.27 ± 0.85 | 0.836 ± 0.0016 a | -0.36 ± 0.096 |
| | Standard | 3.30 ± 2.24 | 0.826 ± 0.0057 b | -0.36 ± 0.153 |
| **Sep 5, 2008** | Control | 8.99 ± 1.16 | 0.822 ± 0.0033 | -0.62 ± 0.041 |
| | Porous | 9.26 ± 1.10 | 0.824 ± 0.0026 | -0.62 ± 0.038 |
| | Standard | 9.47 ± 1.92 | 0.822 ± 0.0043 | -0.51 ± 0.051 |

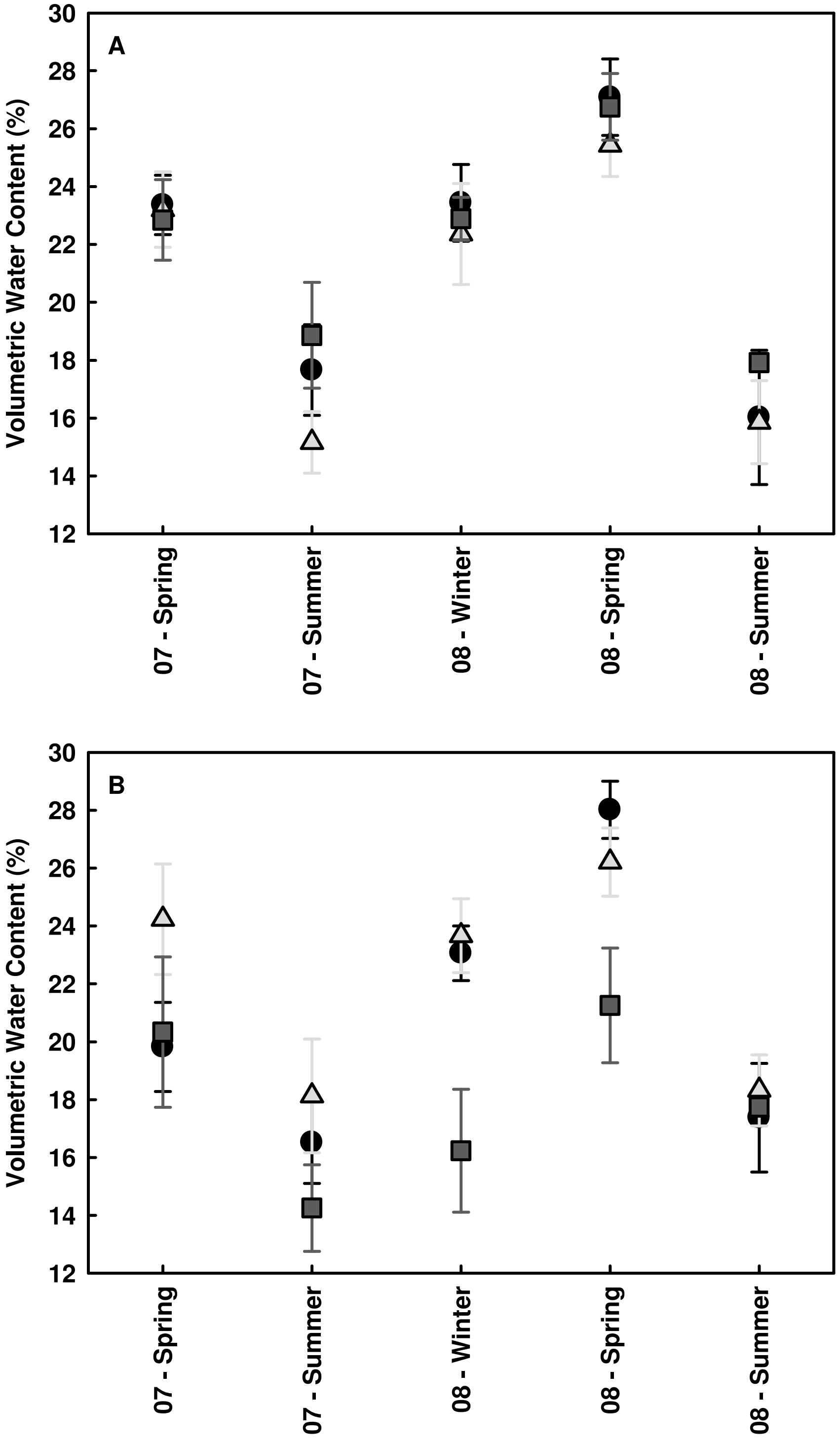

**Figure 1**. Effect of pavement type on seasonal volumetric soil water content (%). A) 5-25 cm soil depth, B) 30-50 cm soil depth. Black circles = control, light grey triangles = porous concrete, dark grey squares = standard concrete. Vertical bars represent ± s.e. for the mean of each pavement treatment.

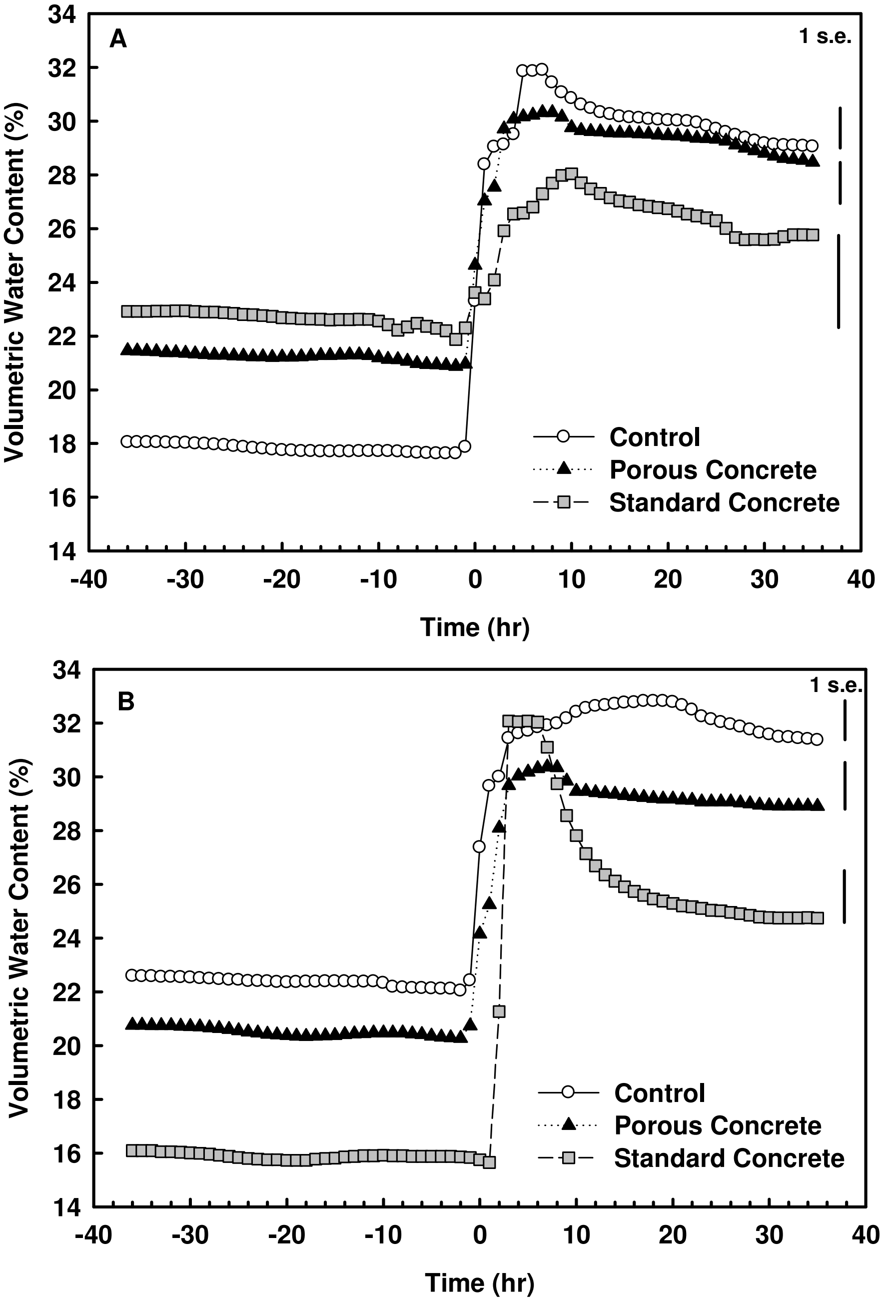

**Figure 2**. Effect of pavement type on hourly volumetric soil water content (VWC, %) before and after a rainfall event that started at time 0 (5/5/08, 12:00). A) 5-25 cm soil depth, B) 30-50 cm soil depth. Vertical bars represent 1 s.e. for each pavement treatment in the order of control, porous, and standard concrete.

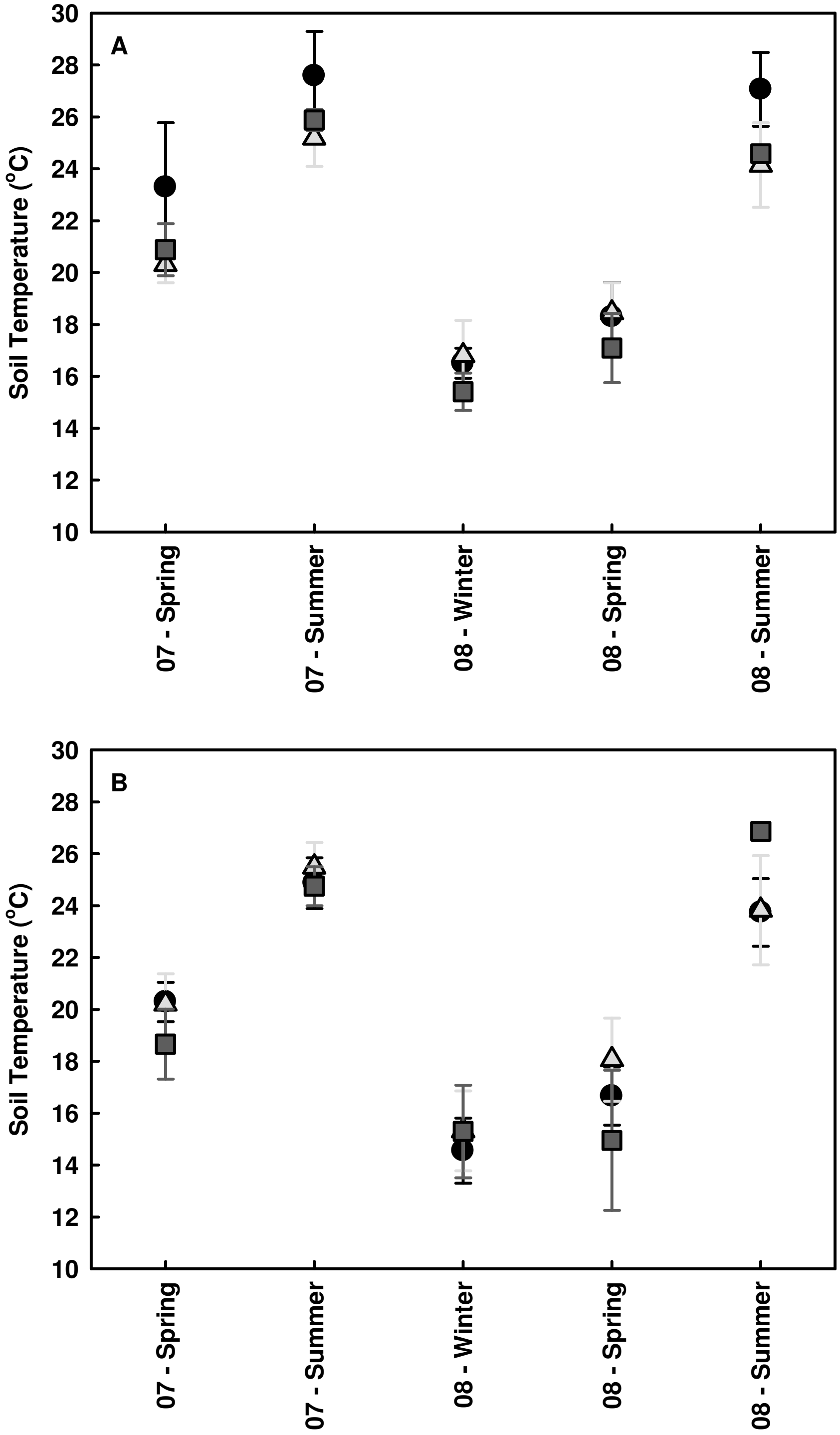

**Figure 3**. Effect of pavement type on seasonal soil temperatures ($^{o}$C). A) 5-25 cm soil depth, B) 30-50 cm soil depth. Black circles = control, light grey triangles = porous concrete, dark grey squares = standard concrete. Vertical bars represent ± s.e. for the mean of each pavement treatment

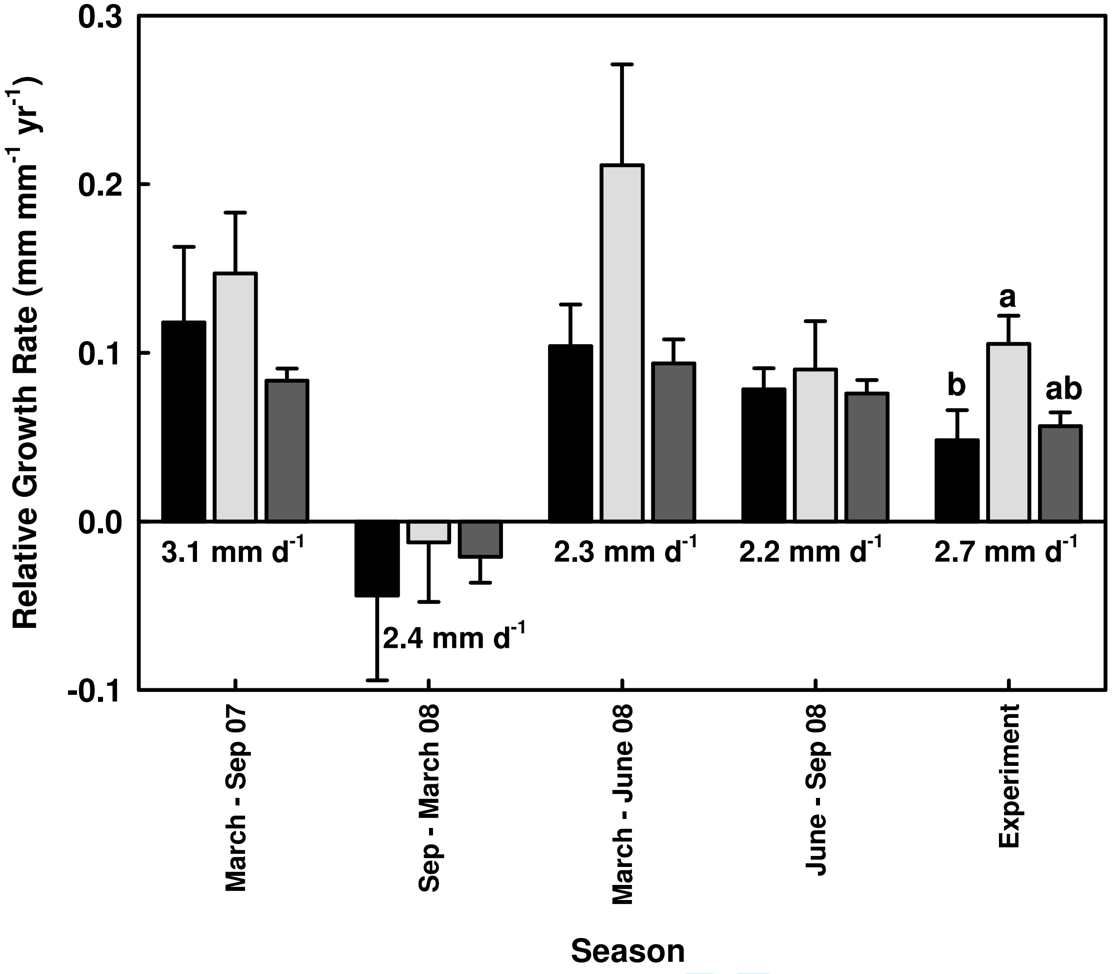

**Figure 4**. Diameter relative growth rates (RGR) of American sweetgum trees as affected by different pavement types. “Experiment” denotes the RGR of the trees over the whole experimental period (9 March 07 – 19 Sep 08). Black bars = control treatment, light grey bars = porous concrete, dark grey bars = standard concrete. Mean daily rainfall rate for each period is printed below each set of bars. Thin vertical bars represent ± s.e. for the mean of each pavement treatment during each period.