

Pervious vs. impervious pavements for sidewalks: effects on soil characteristics and physiology of two establishing urban tree species

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Abstract

The aim of this experiment was to assess the effects of four sidewalk designs, differing in permeability to water and gases, on some soil chemical and physical parameters and on growth and physiology of newly *Celtis australis* and *Fraxinus ornus*. Treatments were: 1) impervious design (asphalt on concrete sub-base); 2) permeable design (curb on crushed rock sub-base); 3) porous design (porous pavement on crushed rock sub-base); 4) control (unpaved soil, kept free of weed by chemical control). Pavements were built in November 2011 and trees were planted in March 2012. Since 2012, soil (temperature, moisture, oxygen content and CO₂ efflux) and plant (growth, leaf gas exchange, chlorophyll fluorescence, water relations) parameters were measured. Results showed that soil traits were highly affected by pavements, while plant traits were less affected, probably because of the little time since planting.

Introduction

Urban development fragments, isolates and degrades natural habitats and disrupts the hydrological cycle (Alberti, 2005). Soil sealing, "the covering of soil by buildings, construction, and layers of completely or partly impermeable artificial materials" is the most pervasive form of land take and it is essentially an irreversible process. During the latest years, soil is being sealed at an unprecedented rate: in Italy, about 8 m² (86.11 ft²) soil are sealed every second (European Commission, 2012). In Europe about 2500000 m² are sealed every day, and the detrimental effects of soil sealing and subsequent soil degradation have been estimated to cost up to 45 billion euro per year (European Commission, 2012). Low albedos of widely used paving materials (i.e. asphalt) trap radiation and cause over-heating, thus contributing to the formation of the urban heat island. Also, the extremely low infiltration rate through impervious pavements triggers runoff and floodings in the urban sites (Dellepetri et al., 2012). Infiltration rate depends on rain intensity, on the slope of the terrain, on soil compaction and, if soil is paved, on the permeability of the sub-grade and of the pavements. Unpaved, uncompacted soils can infiltrate up to 90% of yearly rainfall, but infiltration can be reduced to 5-15% if the soil is covered by asphalt laid on a compacted sub-base. Runoff, by consequence, can increase up to 85% (Monici, 2013). In the latest years, soil sealing has exacerbated some of the deleterious effects of climate change in urban

settings, with floodings increasing in both frequency and intensity (Milly et al., 2002). There is, thus, an urgent need to set guidelines to limit, mitigate, or compensate soil sealing. For this reason, several approaches for the sustainable management of intense rainfall events have been recently developed, including the Sustainable Urban Design Systems (SUDS) in the UK, the Water Sensitive Urban Design (WSUD) in Australia, and the Low Impact Development (LID) in the US. Through a careful analysis of materials (including green areas) and design choices, all these approaches are targeted to maintain permeability coefficient of cities around 60-70%. Because of their extensive use in urban settings, pavements play a major role in urban water balance, and large-scale use of pervious pavement may be critical for a water-wise urban development under a climate change scenario. Two main types of pervious pavements exist (Scholz and Grabowiecki, 2007): 1) permeable pavements: made of impermeable elements, but voids between elements allow water infiltration (e.g. permeable interlocking concrete pavers); 2) porous pavements: made of even aggregates hold together by a permeable binder, are permeable to water along the entire structure (e.g. porous concrete). Clearly, a pervious pavement is not enough and high permeability of the sub-base is also required, or most of the benefits may be neglected (Morgenroth, 2011). Despite of consistent engineering research about technical characteristics of permeable and pervious pavements (Bean et al., 2007; Scholz and Grabowiecki, 2007; Putman and Neptune, 2011), only a very limited number of studies investigated the effects of paving on soil characteristics and on growth and physiology of trees planted in widely paved areas (Volder et al., 2009; 2014; Morgenroth and Burchan, 2009; Morgenroth, 2011; Viswanathan et al., 2011; Weltecke and Gaertig, 2012; Wei et al., 2014; Savi et al., 2015).

Urban green areas provide large ecosystem services to the community: they intercept and store rainfall, and promote infiltration, thus reducing runoff and the risk of floods (Depietri et al., 2012); they cast shade and evaporate large quantities of water, thus contributing to microclimate amelioration and to the reduction of urban heat island effect (Jo and McPherson, 2001; Hardin and Jensen, 2007; Depietri et al., 2012); they assimilate and store large quantities of CO₂, thus contributing to the direct reduction of the concentration in the atmosphere of one of major greenhouse gases (Nowak and Crane, 2002); they purify air by the sequestration of gaseous pollutants and the adsorption of particulate matter (Mori et al., 2015). Finally, they provide a set of economic, psycho-physical, social, and cultural benefits (Kabisch et al., 2015). It is well known, however, that the benefits of trees largely depend on tree health, size, and longevity (Nowak et al., 2002; Ferrini et al., 2014).

It is often observed that tree health is depressed as the amount of sealed soil around the tree increases (Savi et al., 2015). However, the mechanistic reasons of such decline haven't been unraveled yet. Some authors have identified drought as the major cause of decline of trees in sealed areas (Depietri et al., 2012; Savi et al., 2015), because the low infiltration rate through the impervious layer does not allow the recovery of evapotranspirational water losses. Other works, on the contrary, found higher soil water content under pavements than in unpaved soil (Morgenroth and Burchan, 2009; Viswanathan et al., 2011). In these studies, the reduction of evaporation caused by pavements impacted more than low infiltration rate on soil moisture. The effects of

pavements on urban water cycle need to be better addressed, with particular attention to the effect of woody vegetation (i.e. trees planted in paved sites vs. paved soils without trees) on water dynamics. Soil hypoxia and soil CO₂ accumulation under pavements are other possible causes leading to tree decline, through a reduction of root growth and activity (Viswanathan et al., 2011; Volder et al., 2014). Other works, however, found similar or even greater root growth under pavements than under bare soil (Morgenroth, 2011).

Thus, despite of impervious pavements are widespread in the urban environment, there is still a very limited amount of knowledge about the soil-tree-pavement interaction in urban sites. Also, still very limited research has been carried out to evaluate the effect of pervious and porous street designs compared to traditional, impervious pavements. The aim of this work was to compare the effects of sidewalk profile differing in permeability to water and gases on some soil physical characteristics, and on growth and physiology of two newly planted shade tree species. We hypothesized that: 1) soil below impervious pavements may be warmer, because evaporation is impaired; 2) soil moisture may be higher under impervious pavements than in unpaved control in absence of tree roots, but lower where tree roots are present; 3) oxygen availability may be lower, and CO₂ may accumulate in soils covered by impervious pavements; 4) tree growth and leaf gas exchange may be reduced in tree planted in sealed soil because of altered soil temperature and moisture regimes, and depressed gas exchange between soil and atmosphere; 5) negative consequences of soil sealing may be mitigated by using pervious pavements.

Materials and Methods

To test the effects of impervious pavements and possible remedies to reduce soil sealing, an experimental field was built in Vertemate con Minoprio in 2011. Four different sidewalk profiles were compared: 1) impervious design (asphalt on a concrete sub-base); 2) permeable design (curbstone on crushed rock sub-base); 3) porous design (pavement made of coarse aggregate and epoxy resin on crushed rock sub-base); 4) bare soil, kept free of weeds by the use of herbicides. The experimental field is made of 24 (4 treatments x 6 replicates) 50 m² subplots, each of them containing two 1 m² planting holes. Plastic barriers (70 cm deep) were buried between subplots to prevent water movement from one subplot to another. In each subplot, two widely-used shade tree species differing in root regeneration potential (*Celtis australis* L. and *Fraxinus ornus* L., 12-14 cm circumference) were planted. Planting was done in spring 2012. In each plot, polypropylene pipes were inserted through the pavement (close to the planting pits, and in the middle of each subplot) to allow subsequent measurements of soil parameters, as described in Viswanathan et al. (2011). Measured parameters were: 1) soil temperature, measured monthly 25 cm below soil surface with a temperature probe (STP-1, PP-Systems, Amesbury, MA); 2) volumetric soil water content, measured every two weeks at 20 cm and 45 cm depth, in areas of soil with either the presence or the absence of tree roots, using Frequency Domain Reflectometry (FDR) probes; 3) soil CO₂ efflux, measured monthly both within the root-zone and in

soil without roots (i.e. the central part of subplot) with a soil respiration chamber attached to an infra-red gas analyzer (SRC, PP-Systems, Amesbury, MA); 4) soil oxygen concentration, measured using a oxygen probe (OP-2, PP-Systems, Amesbury, MA). Stem diameter at breast height (1.3 m) was measured yearly on all trees. Shoot growth was measured yearly on 20 shoots per species, treatment and block (960 shoot in total). CO₂ assimilation was measured during the growing season (May to September 2013 and 2014) using an infrared gas analyzer (Ciras-2, PP-system, Amesbury, MA, USA) on 3 fully expanded, sun exposed leaves per species, treatment and block (144 leaves in total). Maximum quantum yield of photosystem II (Fv/Fm) was measured on the same leaves as gas exchange, after a 40-min dark adaptation, using a portable fluorometer (HandyPea, Hansatech, King's Lynn, UK).

Results and discussion

Soil temperature and moisture

Soil temperature measured at 25 cm depth was affected by pavement type, by the month of measurement, and a significant pavement x time interaction was found (Fig. 1). During winter months (mainly Dec and Jan) difference in temperature between treatments was low and was mainly determined by pavement color and albedo. Therefore, asphalt and control which were slightly darker than porous were also slightly warmer. From March to November, instead, soil temperature was higher under asphalt and permeable pavement than under porous pavement and control. During this period, differences in temperature were not related to pavement color, but rather to the amount of soil water evaporating through the pavement. The hypothesis that soil temperature may be inversely related to pavement permeability is supported by the primary role of latent heat flux in setting soil temperature (McCumber and Pielke, 1981). Thus, during warmer months, temperature of unpaved soil was always lower than in soil below asphalt and, despite of having similar color, temperature below porous pavements was always lower than below permeable ones. Our results differ from previous works (Volder et al., 2009; Viswanathan et al., 2011), where lower temperature was found below an impervious pavement than below a pervious pavement and in the unpaved control. These studies, however, measured temperature in the shallower soil layers (5 cm below the soil line), where it may be greatly affected by irradiance. To assess the potential role of soil moisture and evaporation on soil temperature, soil volumetric water potential was measured at 20 cm and 45 cm depth in the middle part of each plot, where the soil was not colonized by tree roots (Fig. 2). Soil water content at 20 cm depth was always lower in the unpaved control than below all types of pavement, despite unpaved soils having higher infiltration rates. Reduction of evaporation appears, thus, the main factor leading to higher soil moisture under pavements, in agreement with Morgenroth and Burchan (2009). Differently from these authors, however, we found that pavement type has an effect on shallow soil moisture and evaporation. Soil moisture under permeable pavements and asphalt was higher than under porous pavement and changed very little throughout the year (maximum variation was 8% and 10% in permeable and asphalt treatment, respectively), always remaining near field capacity (Fig. 2, left). On the

contrary, soil moisture declined gradually in control and porous pavement (25% and 20% in control and porous treatment, respectively) when air temperature and VPD increased. These results indicate that all types of soil cover reduced evaporation if compared to bare soil, but porous pavements allowed more water to evaporate if compared to permeable pavements and impervious surfaces. At 45 cm depth, soil moisture was higher in all paved soils than in control (Fig. 2, right). In control plots, soil water content at 45 cm was at field capacity or little below (particularly during the summer period). Under pavements, instead, moisture always exceeded field capacity and in some cases (e.g. July to September for permeable pavements) soils at 45 cm depth were nearly saturated. Interestingly, at 45 cm, soil moisture was lower below asphalt than below permeable pavements, while moisture under porous pavements was more influenced by the period of the year and by climatic parameters.

Tree roots absorb large quantities of water to support transpiration, and transpiration has a greater impact than evaporation of total soil water losses (Amoroso et al., 2010; Sutanto et al., 2012). It is not surprising that soil moisture was lower near the planting pits of both *C. australis* and *F. ornus* when compared to the central part of the plot, where no roots were grown (Fig. 3). Nonetheless, moisture of unpaved soil was in most cases lower than moisture of paved soils. In unpaved soils, soil moisture approached wilting point at 20 cm depth, even if adequate water availability was retained at 45 cm. Pavements generally increased soil moisture at both 20 cm and 45 cm depth even in the presence of tree roots, with soil under porous pavements being in this case moister than soil below permeable pavements (Fig. 3). It must be said, however, that newly planted *C. australis* and *F. ornus* still had most of their roots system in the unpaved planting pits, and long-term investigations are required to assess the effects of expanding root systems on soil water dynamics.

Soil CO₂ efflux and O₂ concentration

Pavements do not only affect soil water content and evaporation, but also gas exchange between soil and atmosphere. CO₂ efflux from soil was higher in plots paved with impervious and, to a lesser extent, permeable pavements when compared to porous pavements and control (Fig. 4, left). Differences among treatments increased during summer months: when higher soil temperature stimulated soil respiration, CO₂ efflux was 3-4 times higher from soils covered with impervious pavements than in control and porous treatments. Higher CO₂ efflux from paved soils has been previously linked to CO₂ accumulation in the soil, because the CO₂ produced by respiration of roots and soil microbiota cannot diffuse to the atmosphere because of the low diffusivity of the pavement (Viswanathan et al., 2011). High CO₂ in the soil is known to inhibit root growth and activity, and to modify pH of root cortical cell, with reversible or irreversible consequences depending on CO₂ concentration (Nobel and Palta, 1989). Soil O₂ concentration was lower under impervious pavement than under other pavement types and control from March to October (Fig. 4, right). The reduction in O₂ caused by the impervious soil cover was, however, much lower than the annual variation of soil O₂ concentration and is likely to have little biological significance (Viswanathan et al., 2011). It must be considered, however, that measurements were conducted during the first 24 months from planting and that long-term experiments are required to

understand if soil O₂ will become limiting or if CO₂ will reach toxic concentrations when most of roots will be grown out of the planting pit under the pavements.

Effects on tree growth and physiology

Effects of pavement type on tree growth were species-specific (Tab. 1). In *C. australis*, DBH growth was unaffected by soil cover type, while shoot growth was, over two years, generally lower in trees planted in unpaved soil than in trees planted in paved plots. In *F. ornus*, DBH growth was unaffected by pavement. Shoot growth, instead, was lower in plants growing with impervious pavements than in those growing with permeable or porous pavements and in unpaved control.

Net photosynthesis (A) and maximum quantum yield of PSII (Fv/Fm) of *C. australis* leaves was generally unaffected by pavement (Fig. 5). The increase of net photosynthetic rate observed from May 2013 (A ~ 8 μmol m⁻² s⁻¹) to September 2013 (A ~ 16 μmol m⁻² s⁻¹) reflects the gradual recovery from transplant shock. These findings were corroborated by fluorescence measurements: Fv/Fm increased from ~ 0.71, corresponding to a moderate to severe stress (Fini et al., 2012), to ~ 0.8, corresponding to relatively healthy plants (optimal values are ~0.82-0.83, see Demming and Bjorkman, 1987), when trees began to expand their roots in the planting pit (Fig. 5). A and Fv/Fm were little affected by pavement type until July 2014. Later on, plants growing in plots covered by impervious pavements had both lower photosynthetic rate and Fv/Fm if compared to plant growing in unpaved plots and in plots covered with permeable and porous pavements. Based on these findings, *F. ornus* was more sensitive than *C. australis* to soil sealing, but differences between species may also be due to different root growth rate and root morphology (i.e. faster root growth in *F. ornus* may have resulted in earlier interaction with pavements than in *C. australis*). Further studies are required to assess the relative tolerance of these species to soil sealing and to identify the effects of soil sealing on established trees.

Conclusions

This experiment investigated the effects of four types of soil cover (three pavements differing in permeability and unpaved control) on soil characteristics and on growth and physiology of newly planted *Fraxinus ornus* and *Celtis australis*. Results showed that covering the soil with impervious pavements increased soil temperature, altered moisture regimes, decreased slightly O₂ availability and resulted in a large accumulation of CO₂ in the soil if compared to unpaved soil. Porous pavements were extremely efficient in mitigating the effect of soil sealing, showing values similar to unpaved control for most measured parameters. Permeable pavements were less effective than porous ones, likely because of low permeability to the outflux of water vapor and CO₂ from the soil.

Despite of the significant effects of soil sealing on soil characteristics, growth and physiology of two newly planted tree species were far less affected. It must be considered, however, that measurements were conducted in the first 27 months after planting, when tree roots were still mostly confined in the soil below the unpaved

planting pit. Long-term research is needed to evaluate how pavement differing in permeability affect growth and physiology of established trees.

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Table 1: Effect of different soil covers on DBH (measured at planting and 18 months after planting) and shoot growth in newly planted *Celtis australis* and *Fraxinus ornus*. Different letters within a tree species indicate significant differences between pavements at $P < 0,05$ (*) o $P < 0,01$ ().**

Species	Pavement	DBH at planting (cm)	Change in DBH 2012-2013 (cm)	Shoot growth 2012 (cm)	Shoot growth 2013 (cm)
<i>Celtis australis</i>	Impervious	4,4 a	0,9 a	33,4 a	30,0 a
	Permeable	4,4 a	0,8 a	33,1 a	21,4 b
	Porous	4,3 a	1,1 a	23,2 b	31,4 a
	Control	4,1 a	0,9 a	22,9 b	19,3 b
<i>Fraxinus ornus</i>	Impervious	4,3 a	0,9 a	17,1 c	8,4 c
	Permeable	4,5 a	0,7 ab	24,9 b	22,2 a
	Porous	4,5 a	0,5 b	49,5 a	16,2 b
	Control	4,5 a	0,6 ab	24,7 b	16,8 b
P _{pavement}		n.s.	n.s.	**	**
P _{species}		n.s.	**	**	**
P _{PxS}		n.s.	*	**	**

Figure 1: Soil temperature measured 25 cm below grade. Monthly values are the average of three different sampling years (2012-2013-2014). Different letters within each sampling date indicate significant differences at $P < 0,01$ () using Duncan's MRT.**

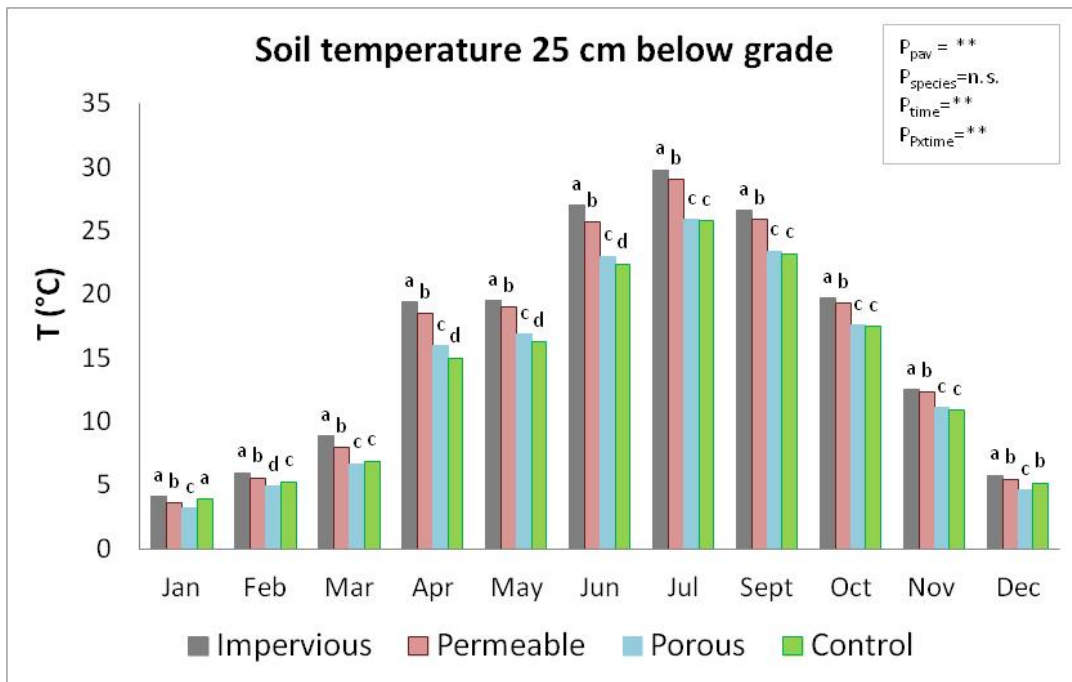


Figure 2: Soil moisture measured at 20 cm (left) and 45 cm (right) below grade, in soil not colonized by roots. Monthly data are the average of three years of measurement (2012-2013-2014). Different letters within the same sampling date indicate significant differences among pavements at $P < 0,01$ () using Duncan's MRT. FC and WP denote field capacity and wilting point, respectively**

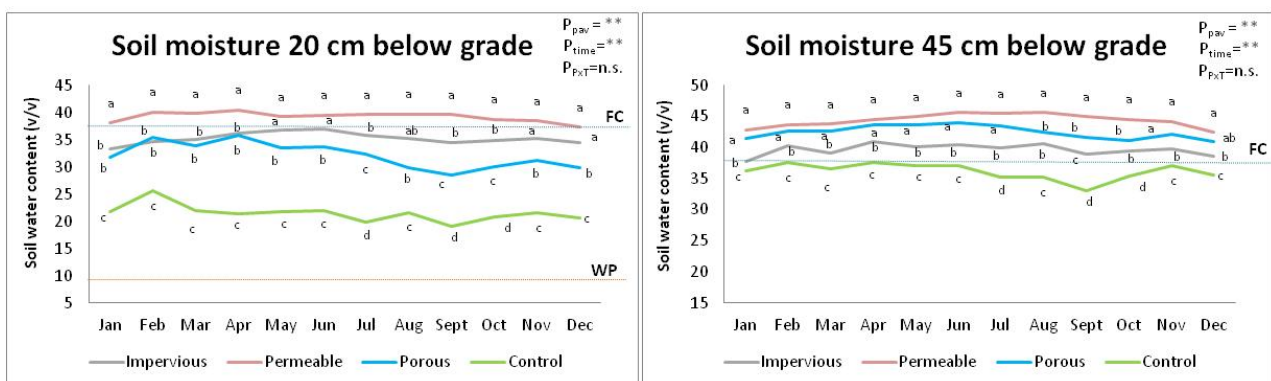


Figure 3: Soil moisture measured at 20 cm (left) and 45 cm (right) below grade, during the summer period (June – September) as affected by different soil covers. Measurements were carried out near the planting pit of *Fraxinus ornus* and *Celtis australis*, and in the central portion of each plot, where no roots were present. Values are the average of measurements conducted during 2013 and 2014. Different letters

indicate significant differences at $P < 0,05$ (*) o $P < 0,01$ (**) using Duncan's MRT. FC and WP denote field capacity and wilting point, respectively.

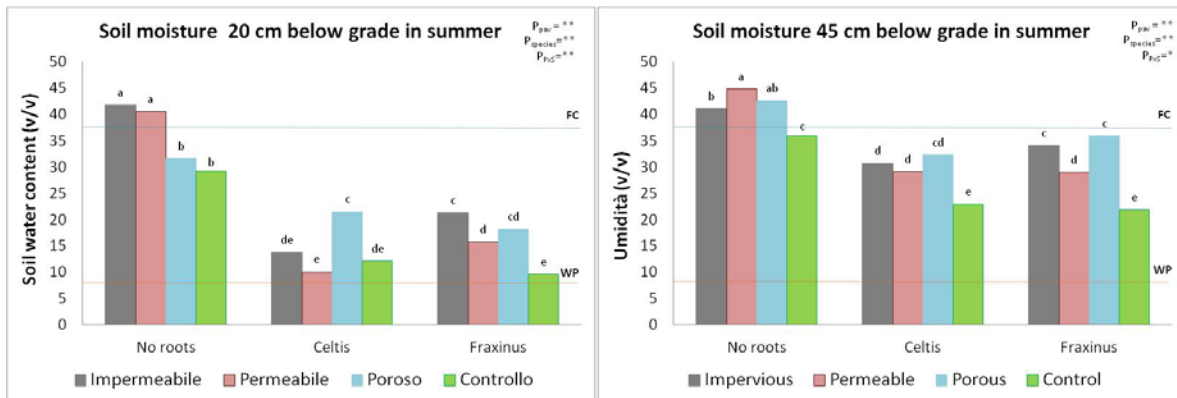


Figure 4: CO₂ efflux from soil (left) and soil O₂ concentration (right) as affected by pavement type. Different letters within the same sampling date indicate significant differences among pavements at $P < 0.05$ (*) and $P < 0.01$ (**). Monthly data are the average of measurement conducted in three consecutive years (2012, 2013, and 2014).

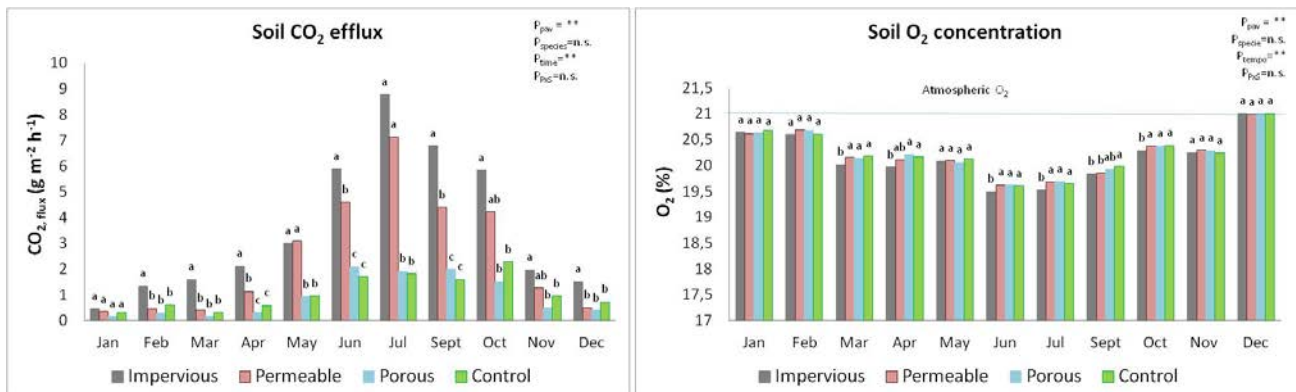


Figure 5: Net photosynthesis (A) and maximum quantum yield of photosystem II (Fv/Fm) in *Celtis australis* and *Fraxinus ornus* planted in soils covered with different pavements. Different letters within the same sampling date indicate significant differences among pavements at $P < 0.05$ using Duncan's MRT

