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Nature based solutions to mitigate soil sealing in urban areas: Results from a 4-year study comparing permeable, porous, and impermeable pavements

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ABSTRACT

Soil sealing is one of the most pervasive forms of soil degradation that follows urbanization and, despite innovative pavements (i.e. pervious) are being installed in urban areas to mitigate it, there is little research on the effects of pervious pavements on soil water and carbon cycle and on the physiology of urban trees. The aim of this 4-year experiment was to assess the effects of three pavements, differing in permeability to water and gases, on some soil physical parameters, and on growth and physiology of newly planted *Celtis australis* and *Fraxinus ornus*. Treatments were: 1) impermeable pavement (asphalt on concrete sub-base); 2) permeable pavement (pavers 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). Soil (temperature, moisture, oxygen content and CO_2 efflux) and plant (above- and below-ground growth, leaf gas exchange, chlorophyll fluorescence, water relations) parameters were measured.

All types of pavements altered the water cycle compared to unpaved soil plots, but this disturbance was less intense in porous pavements than in other soil cover types. Porous pavements allowed both higher infiltration and evaporation of water than both pavers and asphalt. Reduction of evaporative cooling from soil paved with permeable and impermeable pavements contributed to significant soil warming: at 20 cm depth, soils under concrete pavers and asphalt were 4 and 5 °C warmer than soil covered by porous pavements and unpaved soils, respectively. Thus, enhancing evaporation from paved soil by the use of porous pavements may contribute to mitigating urban heat islands. CO_2 greatly accumulated under impermeable and permeable pavements, but not under porous pavements, which showed CO_2 efflux rates similar to control. Soil oxygen slightly decreased only beneath asphalt.

Growth of newly planted *C. australis* and *F. ornus* was little affected by pavement type. Tree transpiration rapidly depleted soil moisture compared to the not-planted scenario, but soil moisture did not fall below wilting point (particularly in the deeper soil layers, i.e. 40–50 cm) in any treatment. While *C. australis* showed similar leaf gas exchange and water relations in all treatments, *F. ornus* showed a depression in CO_2 assimilation and slight signs of stress of the photosynthetic apparatus when planted in soil covered with impermeable pavement.

The effects of soil cover with different materials on tree growth and physiology were little, because newly planted trees have most of their roots still confined in the unpaved planting pit. Still, the reduction of soil sealing around the planting pit triggered the establishment of sensitive species such as ash. Further research is needed to assess the effects of different pavement types on established, larger trees.

Abbreviations: **A**, Net CO_2 assimilation; **C**, soil CO_2 concentration; **Cc**, CO_2 concentration in chloroplast; **Ci**, CO_2 concentration in the substomatal chamber; **E**, transpiration; $\mathbf{g_m}$, mesophyll conductance to CO_2 diffusion; $\mathbf{g_{sc}}$, stomatal conductance to CO_2; $\mathbf{g_{sw}}$, stomatal conductance to water vapor; **J**, soil CO_2 efflux; $\mathbf{K_{leaf}}$, leaf hydraulic conductance;$\mathbf{K_{plant}}$, plant hydraulic conductance; $\mathbf{K_{sx}}$, soil to xylem hydraulic conductance; $\mathbf{O_{2soil}}$, soil oxygen content; $\mathbf{RGR_{stem}}$, stem relative growth rate; $\mathbf{R_{soil}}$, soil respiration; $\mathbf{T_{soil}}$, soil temperature; $\mathbf{T_{leaf}}$, leaf temperature; $\boldsymbol{\psi_m}$, midday water potential; $\boldsymbol{\psi_x}$, xylem water potential; $\boldsymbol{\psi_w}$, pre-dawn water potential; $\boldsymbol{\theta_{20}}$, soil moisture at 20 cm depth; $\boldsymbol{\theta_{45}}$, soil moisture at 45 cm depth

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1. Introduction

In this Anthropocene era, urban settings and their related grey infrastructures have expanded at unprecedented rate, becoming a huge sink of natural resources (including soil) and a massive source of externalities (Konijnendijk et al., 2016). In particular, soil sealing, defined as the covering of soil by buildings, constructions, and layers of completely or partly impermeable artificial materials, is one of the most pervasive and irreversible forms of soil degradation that follows urbanization (Scalenghe and Marsan, 2009). Over the period 1990–2000, in Europe about 1000 km^2 were sealed every year and, although this trend has been recently cut back to 900 km^2 per year, the detrimental effects of soil sealing and the subsequent environmental degradation have been estimated to cost up to 45 billion euro per year in Europe (European Commission, 2012).

First, through its influence on soil hydrology, soil sealing exacerbates the risk of flash floods from intense rain events, which are indeed more and more frequent because of climate change (Milly et al., 2002; Barthel and Neumayer, 2012; Marafuz et al., 2015). In Leipzig, runoff more than doubled over the period 1940–2003 due to the increase in impervious surfaces (Haase and Nuissl, 2007). In Leeds, a 12.6% increase in sealed soil increased runoff by 12% (Perry and Nawaz, 2008). Not only the water cycle, but also soil-gas migration and gas exchange between soil and atmosphere are affected by soil sealing, but little research focused on this issue until very recent years (Viswanathan et al., 2011; Weltecke and Gaertig, 2012). Second, impermeable materials used for pavements and buildings are often characterized by low albedo and large thermal admittance and capacity. These factors were shown to increase sensible heat within urban boundaries and to be major drivers of the Urban Heat Island (UHI) effect (Oke et al., 1989; Asaeda and Ca, 2000; Kleerekoper et al., 2012).

Third, the effects of soil sealing on biogeochemical cycles (especially carbon) are still poorly understood, but there is evidence that soil sealing induces a major shift in soil carbon stock from organic to inorganic carbon, and a general depression of soil organic carbon. Soil potential carbon mineralization rate, basal respiration, and microbial activity are also severely depressed in sealed soil, which indeed limits soil fertility, long term carbon storage and, overall, provision of ecosystem services from the soil (Wei et al., 2014).

The importance of urban areas as living environments for most humans has been recognized in the 2015 United Nations Sustainable Development Goals (United Nations, 2015). Goal no. 11, specifically, highlights the need of 'Making cities inclusive, safe, resilient and sustainable' (Konijnendijk et al., 2016). Changes occurring below ground and at the soil-atmosphere interface have an impact on urban ecosystem as a whole, including humans, and the more human activities disrupt natural cycles and processes, the less the urban ecosystem is self-sustaining, resistant and resilient to the ongoing global change (Grimm et al., 2008; Qiu et al., 2015). For example, in Europe, despite large investments in flood protection, several major floods have occurred in the latest years, with multiple fatalities and material damages accounting for billions of euros (Kundzewicz et al., 2014). Similarly, 3–8% of electricity demand in the United States is used yearly only to compensate for the UHI effect (McPherson, 1994). Also, UHI increases the number of hot days, thus inducing higher vulnerability to thermal stress in urban dwellers compared to those living outside the urban setting (Harlan et al., 2006; Tan et al., 2010; Tomlinson et al., 2011). In spite of the environmental changes induced by soil sealing, humans definitely needs pavements to support daily activities and maintain the actual quality of life, and hard surfaces can comprise as much as 67% of urban surface areas, while green areas can fall as low as 16% in several cities (Matthews et al., 2015). To this regard there is a growing recognition that preserving and re-establishing nature can help provide viable solutions in a smart "engineered" way (European Commission, 2015).

Nature-based solutions (NBS) are living solutions inspired by, continuously supported by and using nature, designed to address various societal challenges in a resource-efficient and adaptable manner and to provide simultaneously economic, social, and environmental benefits (Maes and Jacobs, 2015). In heavily degraded sites, such as the urban environment, type III NBS (*sensu* Eggermont et al., 2015) have the aim of rehabilitating bio-ecological cycles, to restore and enhance sustainability. Pervious pavements have recently gained interest as type III NBS to restore water and carbon cycle in urban sites (European Commission, 2015).

Two main types of pervious pavements exist (Scholz and Grabowiecki, 2007): 1- permeable pavements (e.g. interlocking concrete pavers) are made of impermeable modular elements, but voids between elements allow water infiltration and soil-atmosphere gas exchange; 2- porous pavements (e.g. porous concrete), instead, are made of even-graded inert bound by a permeable binder (e.g. epoxy resin), and are permeable along their entire surface.

While considerable engineering research has been done to elucidate the technical characteristics of permeable and porous pavements (see for example: Bean et al., 2007; Scholz and Grabowiecki, 2007; Putman and Neptune, 2011), there is only a limited number of studies investigating the effects of impermeable and pervious pavements on the different components of the urban ecosystem, including soil and trees (Volder et al., 2009, 2014; Morgenroth and Buchan, 2009; Morgenroth, 2011; Viswanathan et al., 2011; Weltecke and Gaertig, 2012; Savi et al., 2015).

There is consistent empirical evidence that soil sealing around the trees depresses tree health, but reasons of such decline haven't been unraveled yet. Some authors have identified drought as the major cause of tree decline in sealed areas (Savi et al., 2015), but higher soil water content under pavements than in bare soil was found in other works (Morgenroth and Buchan, 2009; Viswanathan et al., 2011). Soil hypoxia and soil CO_2 accumulation beneath impermeable pavements have also been hypothesized as possible causes leading to tree decline, because they can reduce 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).

If soil sealing has lead to excessive simplification of the urban ecosystem, where element cycling is impaired and vegetation growth depressed, the implementation of green, high permeable alleys may help its revitalization and promote sustainability (Newell et al., 2013; Mullaney et al., 2015). To address this issue, we tested the hypotheses that: 1) soil sealing with impermeable material depresses water and gas exchange between soil and atmosphere, resulting in altered oxygen, water, and carbon dioxide concentration in sealed soils compared to the unpaved ones; 2) permeable and porous pavements can be effective NBS to mitigate the impact of paving on water and carbon cycle, thus promoting sustainable urbanization; 3) higher pavement permeability around the planting pit improves tree health and growth, and the community can co-benefit of the enhanced delivery of ecosystem services by urban trees.

2. Materials and methods

2.1. Site description

The research was carried out at Fondazione Minoprio (Vertemate con Minoprio, CO, Italy). Average annual rainfall and temperature in the study site measured over the 1996–2015 period are 1106 mm and 13.3 °C, respectively (see Fig. A.1 in supplemental material for monthly rainfall and average temperature over the experimental period). Soil is a slightly alkaline sandy silt topsoil with low lime and an average organic matter content (see Table 1 for details).

In November 2011, a 1200 m^2 experimental field was divided into 24 sub-plots (50 m^2 area each). Polypropylene barriers (70 cm deep)