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Pavement induced soil warming accelerates leaf budburst of ash trees

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ABSTRACT

Urban greening is becoming increasingly popular in cities around the world, which is leading to the planting of more and more trees in paved areas in urban environments. However scientifically it is not well understood how pavement may impact tree greening efforts. In this paper, we investigated plant responses to pavement in the suburb of Changping District, Beijing, China. We planted the popular deciduous ash tree (*Fraxinus chinensis*) in three different pavements: pervious bricks; impervious bricks; and no pavement (i.e., control) at three densities (0.5 m × 0.5 m, 1.0 m × 1.0 m, and 2.0 m × 2.0 m apart). We investigated the influence of pavement type on plant phenology by monitoring soil temperature and moisture as well as leaf budburst rate from January to April in 2014. Our results show that pavement can significantly increase soil temperature, and decreased soil moisture except pervious pavement at the 1.0 m × 1.0 m density. The significant relationship between the leaf budburst rate and accumulated soil temperature implies that pavement induced soil warming can accelerate leaf budburst, suggesting that pavement contributes to tree leaf budburst acceleration by probably both increasing soil and air temperatures in urban environments.

1. Introduction

The majority of urban environments are paved in order to provide residents efficient and safe built infrastructure like parking lots, roads and driveways, which are important for urban transportation. A pavement is defined as the land in urban environments covered with artificial materials like concrete, asphalt and bricks (Viswanathan, 2010). Although pavements are convenient for social and economic activities, pavements are known to have adverse impacts on the environment, including increasing stormwater runoff due to the reduction in water infiltration (Lee and Heaney, 2003), enhancing air and ground surface temperature due to greater absorption of short-wave radiation by low reflectivity surfaces (Asaeda et al., 1996) and reducing evaporative cooling rates of soil and plants (Viswanathan, 2010), blocking soil-air gas exchange (Feng et al., 2002), and reducing carbon storage (Zhao et al., 2012). The expansion of pavement reduces the land available for building green infrastructure and growing trees. Trees can provide many services to help mitigate the adverse effects of pavements in urban environments (Ridder et al., 2004). These include reducing stormwater flows by increasing rainfall interception (Xiao and McPherson, 2002), reducing the urban heat island effect through evaporative cooling and shade provision (Shashua-Bar et al., 2010; Viswanathan, 2010), improving air quality via absorption of particulate pollutants (Beckett et al., 1998) and reducing noise (Lohr et al., 2004). Thus urban afforestation is becoming a common practice in many cities. In China, urban green space coverage has increased from 16.9% in 1986 to 23.0% in 2000, and the area per capita has increased by 3 m^2 between 1986 and 2000 (Wang, 2009). Furthermore the area of green space has shown net increases in three major UK cities from 1991 to 2006 (Dallimer et al., 2011). New York City, USA launched the Million Trees NYC initiative to plant 600,000 trees, which include street trees and approximately 809 ha of forest restoration (New York City Department of Parks and Recreation, 2007).

Because most of urban land has been paved for providing transportation and human activity and the amount of available unbuilt land for tree planting is very limited in cities, many trees have to be planted in paved environments. Unfortunately, trees planted in impervious pavement often have poorer growth (Mueller and Day, 2005), and even more 50% decrement of shoot and root growth than those in the field (Grabosky et al., 2001). Compared to vegetated surfaces, impervious pavements can store more heat and conduct the heat into the soil layer increasing the soil temperature (Tang et al., 2011), which may weaken root growth and even kill tree roots when temperatures are too high (Celestian and Martin, 2004).

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Impervious pavements restrict water penetration into the rhizospheric soil of trees thereby decreasing water availability for tree uptake (Kozlowski, 1999; Balakina et al., 2005; Mueller and Day, 2005). Impervious pavement also can affect soil physiochemical properties, nutrient availability, and microbial characterizations, which can result in the reduction of soil net potential mineralization and nitrification (Zhao et al., 2012).

In recent years, one approach to make the soil beneath pavements more conducive to tree growth is to use pervious surfaces such as porous concrete, porous asphalt and permeable interlocking concrete pavers (Volder et al., 2009; Morgenroth and Visser, 2011; Mullaney and Lucke, 2014; Mullaney et al., 2015). The pores of pervious surfaces can facilitate the movement of water through the surface into the soil profile (Bean et al., 2007; Dietz, 2007). Pervious pavements could increase tree stem height, diameter, and biomass of Oriental Plane tree seedlings (Morgenroth and Visser, 2011). However, the results are not always consistent for all experiments. Root biomass was significantly enhanced beneath pervious pavements relative to impervious pavements in the absence of a compacted subgrade and gravel base, but was unaffected by pavements when there was a compacted subgrade and gravel base (Morgenroth, 2011). The relative growth rates of tree trunk diameters were similar across three different pavement types (no pavement, pervious porous concrete and impervious standard concrete pavements) (Volder et al., 2009). Therefore, we design a factorial split plot experiment to verify the different effects between pervious and impervious pavement on environment and tree growth.

Plant phenology, which is the timing of plant growing events (e.g., leaf budburst, flowering, coloration, and falling), is an important indicator for describing plant responses to environmental changes such as variations in air temperature, photoperiod, precipitation, soil moisture, and evaporation (Zhao and Schwartz, 2003; Neil and Wu, 2006; Cleland et al., 2007). However, there are few investigations on plant phenology in response to pavement in urban environments. Leaf budburst is an important plant phenological phase since it marks the starting period of tree growth in a new year, and is known to be one of the most sensitive indicators to environmental change (Neil and Wu, 2006; Doi and Katano, 2008). Air temperature is recognized as the dominant factor controlling leaf budburst (Menzel and Fabian, 1999; White et al., 2002; Primack et al., 2004; Zhang et al., 2004). In urban areas, it has been reported that pavement enhances the air temperature because it stores more energy than vegetation (Kjelgren and Montague, 1998; Hung et al., 2006). Leaf budburst would be accelerated because the rate of pavement induced urban warming is much greater than the global average climate warming as a result of the impervious concrete surfaces (Luo et al., 2007). This is attributed to the urban heat island effect where impervious surfaces hold heat more than pervious surfaces and thus the air temperature in urban areas is often increased compared to rural areas. A large number of studies reported that the spring greening in urban environments is earlier than in the suburbs due to urban heat island effect (Roetzer et al., 2000; Fitter and Fitter, 2002; White et al., 2002; Zhang et al., 2004). Anecdotal observations have shown that springs are warmer in recent decades (Zhang et al., 2005), leading to notable advancement in leaf budburst. For instance, the leaf budburst dates have advanced during the past five decades in four Japanese localities (Doi and Katano, 2008). In China, the advancements of the starting date of tree greening have been reported in highly urbanized regions, such as in the Yangtze River Delta Region (Han et al., 2008) and in Beijing (Luo et al., 2007).

Overlying pavements could alter the trees growing environment not only by increasing air temperature, but more importantly, by changing the physical and chemical characteristics of the soil (Celestian and Martin, 2004; Morgenroth et al., 2013). However, there has been no investigation on the impacts of pavements on plant phenology (e.g., leaf budburst) in relation to the soil microenvironment, specifically soil temperature and moisture. The direct influence of pavement induced environmental factors other than air temperature on leaf budburst acceleration in urban areas is largely unknown.

This paper aims to investigate seedling responses to different pavement environments with different planting densities. Soil temperature and moisture and leaf budburst rate were monitored to address the following questions: (1) What changes to soil temperature and moisture and leaf budburst can occur under pavements? (2) What factors contribute to phenological changes because of pavement? (3) Are there differences in spring soil temperature and moisture and leaf phenology between pervious and impervious pavement?

2. Materials and methods

2.1. Site description

A field experiment was conducted at Zhangtou village, Changping District, Beijing, China (40°12′N, 116°08′E). It is a temperate continental monsoon climate, with four distinct seasons. The average annual rainfall is 542 mm with the majority of the rainfall occurring from June to September. Annual mean temperature is 12.1 °C and the maximum and minimum air temperatures are 41.4 °C and −19.6 °C, respectively (Local Chronicles Office of Changping District of Beijing, 2012). The soil texture at the test site is defined as sandy loam, and the bulk density is 1.5 g cm^{-3}, mean soil organic matter content is16.4 g kg^{-1}, total nitrogen 0.9 g kg^{-1}, available phosphorus 38.1 mg kg^{-1}, available potassium 102.1 mg kg^{-1}, and soil pH value 8.3 (Tong et al., 2011).

2.2. Experimental design

A factorial split plot experimental design was used to divide the study area into three equal zones along the width edge for three pavement types: (1) pervious bricks pavement, (2) impervious bricks pavement, and (3) no pavement (i.e., control). In each zone, we used three blocks as replicates, and within each block we had three plots with different densities: (1) 23 trees with a density of 0.5 m × 0.5 m, (2) 23 trees with a density of 1.0 m × 1.0 m, and (3) 18 trees with a density of 2.0 m × 2.0 m. In summary there were nine different treatments (three pavements and three densities) with three replicates (Fig. 1). The plot areas were 9, 25, and 80 m^2 for 0.5 m × 0.5 m, 1.0 m × 1.0 m, and 2.0 m × 2.0 m plant density, respectively. Zones were segregated by a shallow drainage ditch. Prior to the experiment, the land was cultivated for wheat and maize production for many years. The land zones for treatments of pervious and impervious pavements were compacted and leveled before the bricks were paved. All bricks were paved tightly on the soil surface side by side. The gaps between bricks were filled with clay soil to prevent water infiltration. Pits of 20 cm × 20 cm were created before the bricks were paved to plant the trees according to the different densities. All bricks are grey, and the size was 20 cm × 10 cm × 6 cm (length × width × height). The bricks were produced from a mixture of clay, sand, and coal ash by Beijing Yataiyuhong Technology Development Co., Ltd. Due to a different mixing ratio, the pervious brick has a coarse surface and is porous while the impervious brick surface is smooth and not porous. The pervious capability of pervious bricks is more than 0.4 mm s^{-1} (manufacturer data).

One year old ash tree (*Fraxinus chinensis*) seedlings were randomly planted on April 16, 2012. Ash trees were chosen as they are a common urban tree species in Beijing. Before the trees were planted