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Research Paper

Tree survival and growth are impacted by increased surface temperature on paved land

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HIGHLIGHTS

- Pavements could significantly increase surface temperature.
- Soil moisture responses to pavement varied with tree species and spacing.
- Surface temperature and soil moisture both decreased with decreasing tree spacing.
- The presence of pavements reduced tree growth including height and basal diameter.
- Pervious pavement may not alleviate the reduction in tree growth due to heat stress.

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ABSTRACT

Trees are increasingly planted within paved environments in cities. However, little is known regarding growth responses of trees to different pavements. In this study, three popular urban forest tree species, pine (*Pinus tabuliformis Carr.*), ash (*Fraxinus chinensis*), and maple (*Acer truncatum Bunge*), were planted on different paved and unpaved plots (pervious brick pavement, impervious brick pavement, and no pavement as the control) at three different spacing (0.5 m × 0.5 m, 1.0 m × 1.0 m, and 2.0 m × 2.0 m apart). Results showed that pavement significantly increased surface temperature, changed soil moisture, and decreased survival rate of maple, and height and basal diameter increments of all three species, except for ash at the 0.5 m × 0.5 m spacing. There were significant interactions between pavement and spacing on tree height and basal diameter increments. Linear regression analysis showed that increased surface temperature was the primary contributor to decreased tree survival and growth. Therefore, alleviating the increased surface temperature induced by the pavement is important for guaranteeing tree survival and growth.

1. Introduction

Urban trees can provide a wide range of ecosystem services to enhance the quality of life for residents (Ridder et al., 2004). They can reduce storm water flow by increasing rainfall interception (Xiao & McPherson, 2002), alleviate urban heat island effects by increasing evaporative cooling and providing shade (Mullaney, Lucke, & Trueman, 2015; Shashua-Bar, Potchter, Bitan, Boltansky, & Yaakov, 2010), improve air quality by absorbing gas and particulate pollutants (Beckett, Freer-Smith, & Taylor, 1998), and reduce noise by absorbing sound and providing quiet environments (Lohr, Pearson-Mims, Tarnai, & Dillman, 2004). However, trees are typically surrounded by impervious pavements such as parking lots, roads, and driveways, which can alter soil microenvironments through increased soil surface and rhizospheric temperature (Arnfield, 2003; Tang et al., 2011), decreased rainwater infiltration (Lee & Heaney, 2003), blockage of soil-air gas exchange (Balakina et al., 2005; Feng, Wu, & Letey, 2002), reduced nutrient availability (Zhao, Li, Wang, Yang, & Ni, 2012), and altered energy and water balances (Morgenroth & Buchan, 2009). Trees planted in and around areas of impervious pavement often have poor growth and shorter life spans than trees growing in natural environments and thus generally require more protection (Bühler, Kristoffersen, & Larsen, 2007; Volder, Viswanathan, & Watson, 2014). Researchers

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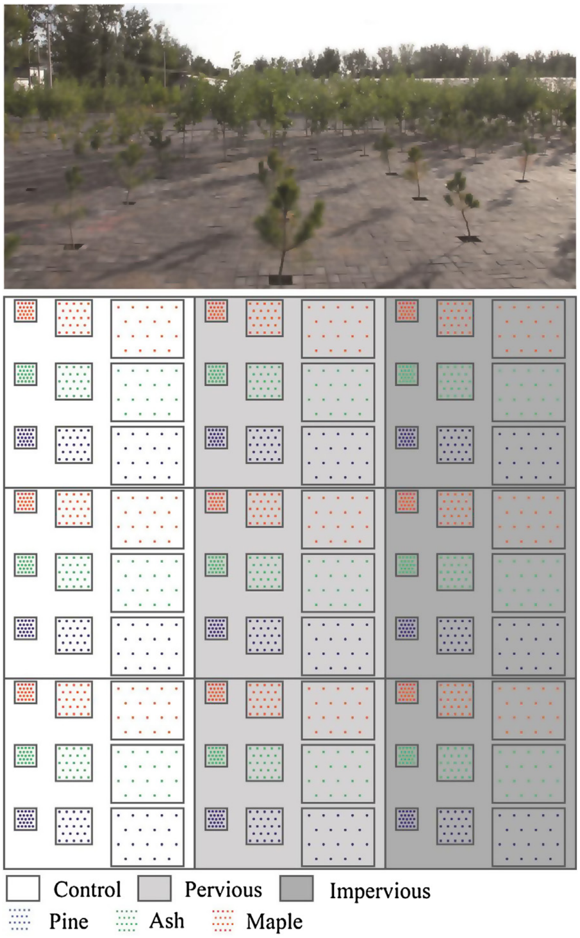

Fig. 1. A photograph of a sample plot (upper) and a diagram of the experimental design (lower).

have found that the survival, health, and growth rates of urban trees are influenced by both site characteristics and human activity (Lawrence, Escobedo, Staudhammer, & Zipperer, 2012; Lu et al., 2010). Berrang, Karnosky, and Stanton (1985) found that poor tree growth was often associated with insufficient water availability, and that impervious surfaces could affect tree growth by restricting water from infiltrating into the soil, thereby decreasing water availability for tree uptake (Balakina et al., 2005; Kozlowski, 1999; Mueller & Day, 2005). Impervious pavements can also store more heat and cause higher temperatures in the upper soil layers (Tang et al., 2011), which may weaken root growth and even kill tree roots when temperatures are too high (above 40 °C) (Celestian & Martin, 2004; Martin & Ingram, 1991).

Tree growth rate and health growing under impervious pavements are generally threatened (Grabosky, Bassuk, Irwin, & Van Es, 2001). Mueller and Day (2005) showed that trees planted in open lawn sites have better growth than those in sites surrounded by impervious pavements. In addition, the height and diameter at breast height of trees in nonpaved surfaces are often higher in the comparison to areas of impervious pavement (Grabosky & Gilman, 2004; Mullaney et al., 2015; Rahman, Stringer, & Ennos, 2013). Furthermore, trees grown on pavements in urban environments face compounding stresses, such as restricted soil moisture extremes (Berrang et al., 1985), soil temperature (Graves, 1994), soil compaction (Philip & Azlin, 2005), soil chemicals pollution (Marosz & Nowak, 2008), air pollution (Su & Sun, 2006), species tolerance (Lu et al., 2010), and physical injuries to stems and branches of plants (Lakovoglou, Thompson, Burras, & Kipper, 2001).

Higher water availability, lower temperatures, and higher root zone oxygen typically improve the health and growth of trees (Balakina et al., 2005; D'Amato, Sydnor, Knee, Hunt, & Bishop, 2002; Kozlowski, 1999). Therefore, researchers have proposed using pervious pavement (pervious materials including gravel, crushed stone, open paving blocks, and porous bricks) instead of impervious pavement to support soil conditions beneath pavements that are more conducive to tree growth (Morgenroth & Visser, 2011; Mullaney & Lucke, 2014; Mullaney et al., 2015; Volder, Watson, & Viswanathan, 2009). Compared to impervious pavements, pervious pavements have high infiltration rates of water and oxygen, which help reduce the stress experienced by urban trees (Bean, Hunt, & Bidelspach, 2007; Dietz, 2007). This could potentially improve productive conditions for tree root growth and activity (Morgenroth, 2011; Viswanathan, Volder, Watson, & Aitkenhead-Peterson, 2011). Morgenroth and Visser (2011) also showed that pervious pavements could increase tree stem height, diameter, and biomass of oriental plane tree seedlings. However, results were not always consistent for all studies. Volder et al. (2009) found that the relative growth rates of tree trunk diameters were similar across three different pavement types (no pavement, pervious, and impervious pavements).

Although several studies have focused on identifying the influence of different pavement types on tree performance (Morgenroth & Visser, 2011; Viswanathan et al., 2011; Volder et al., 2009), these have mostly been studies of single tree species without consideration of spacing influences. Most of the previous studies also have used *in-situ* measurements, which have specific limitations due to uncontrolled interference from the surrounding environment and human activity.

The objective of this study was to investigate how pavements with varying spacing would affect the growth of urban seedling trees. The field study was established to test the following hypotheses: (1) soil moisture under pervious pavement is greater than under impervious pavement and non-pavement, (2) the survival rates of trees in plots with pervious pavement are higher than impervious pavement, and (3) trees growing in pervious pavement will exhibit greater height and diameter growth than those growing in impervious pavement. The results of this study have the potential to assist urban landscape designers and urban foresters in designing and managing pavement systems that improve the growth of trees planted in urban environments.

2. Methods

2.1. Site description

The field experiment was conducted at Zhangtou village, Changping District, Beijing, China (40°12′N, 116°08′E). The area has a temperate continental monsoon climate with four distinct seasons. The mean annual rainfall is 542 mm with the majority of rainfall occurring from June to September. The mean annual 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 16.4 g/kg, total nitrogen 0.9 g/kg, available phosphorus 38.1 mg/kg, available potassium 102.1 mg/kg, 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 (previous cropland) into three equal zones for three pavement types: (1) pervious bricks pavement, (2) impervious