Urban Ecosystems (2018) 21:691–696
https://doi.org/10.1007/s11252-018-0750-1

Effects of ground surface permeability on the growth of urban linden trees

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Published online: 15 March 2018

Abstract

Street trees are an important part of urban vegetation due to their provisioning of different types of ecosystem services such as local climate regulation and contribution to aesthetical and recreational values. In order to provide these services, urban trees need to endure many stress factors not present in natural environments, such as the widespread use of impervious surfaces in the vicinity of street trees. However, few studies have evaluated the effect of this potential stress factor on urban tree growth. The aim of this study was therefore to investigate how ground surface permeability affects stem and current-year shoot growth of linden (*Tilia europaea*) street trees in Gothenburg, Sweden. We found that a small fraction of permeable ground surface in the vertically projected tree crown area caused lower stem growth and strongly suppressed current-year shoot growth. This finding can guide future city planning, demonstrating that the vitality of street trees is compromised when the permeable surface area in the vicinity of the tree is small.

Keywords Permeability · Urban trees · Tree growth · *Tilia*

Introduction

Urban trees provide locally generated ecosystem services such as filtering the air from pollutant gases and harmful particles, micro-climate regulation by shading and transpiratory cooling, creation and preservation of biodiversity, and recreational and aesthetic values for the inhabitants of cities (Bolund and Hunhammar 1999; Sjöman and Slagstedt 2015). However, ecosystem services provided by urban trees are often limited by poor tree vitality (May and Livesley 2013) and street trees often have high mortality rates and short average lifespans compared to trees growing in natural conditions (Roman and Scatena 2011). A large number of interacting factors can influence the growth rate and vitality of urban trees, including soil and air pollution, excess heat, funneled strong winds, and shading by surrounding buildings.

Furthermore, the soils in urban areas are often poor, and tree root systems may have to endure limited soil volumes and ground compaction, constraining plant availability of both oxygen and water (Konijnendijk et al. 2005). Humans also directly damage trees by infrastructure installations and maintenance work, vandalism and car accidents (Konijnendijk et al. 2005; Mullaney et al. 2015).

Several studies have shown that impervious surfaces such as pavement in the near vicinity of tree stems can negatively influence the water availability, vitality and growth of urban trees (Roberts 1977; Jim 1997; Iakovoglou et al. 2001; Quigley 2004; Schröder 2008; Gillner et al. 2014; Konarska et al. 2015). In cities, much of the precipitated water is directly lost through surface runoff into storm drains, potentially causing severe water shortage of trees growing in areas where only a small fraction of the ground is permeable (Gillner et al. 2014, Konarska et al. 2015). In addition to negative effects on tree water supply, impervious surfaces may also negatively affect urban trees through enhanced extreme soil and air temperatures. Soil temperatures can become particularly high in larger paved areas exposed to high levels of solar radiation, leading to exceedance of root tissue heat tolerance thresholds and

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inhibited root growth (Celestian and Martin 2004; Graves 1994). In addition, the air above impervious surfaces, such as asphalt, is also usually warmer and drier than air above natural ground, potentially causing reduced stomatal conductance, photosynthesis and tree growth (Montague and Kjelgren 2004; Mueller and Day 2005). Finally, the aeration of the soil is poor below impervious surfaces, potentially causing oxygen deficiency in tree roots (Wiseman 2004).

Few studies have explicitly investigated how tree performance is related to the fraction of permeable ground surfaces within the vertically projected tree crown area. While a large study with 600 trees in New Jersey, USA, failed to detect any significant relationship between the permeable surface cover and tree growth across nine tree species (Vrecenak et al. 1989), other investigations reported enhanced growth and gas exchange of trees surrounded by grass or bare soil compared to those planted over paved surfaces (Celestian and Martin 2005; Ferrini and Baietto 2007; Grabosky and Gilman 2004; Konarska et al. 2015; Sanders et al. 2013). Clearly, further studies are needed to investigate the links between ground surface permeability and tree functioning, and whether such possible effects are gradual or limited to the most severe cases of impermeability only.

With the overall aim of assessing the influence of planting design on the vitality of street trees, we investigated how the fraction of permeable ground surface below the tree crown affects stem and shoot growth of linden trees (*Tilia europaea*) in Gothenburg, Sweden. The study focused on street trees, which are exposed to more stressful growing conditions than park trees.

Materials and methods

Site description and plant material

The study was conducted in Gothenburg (57°42′N, 11°58′E), the second largest city in Sweden, located on the west coast of the country. The city has a maritime temperate climate with mean daily air temperature of 17.0 °C in July and −1.1 °C in February, and a mean annual precipitation of 758 mm (SMHI 2014). Gothenburg is a relatively green city with a green area (defined as un-built land over 1 ha) of 55%. In the central area of the city, park and street trees are dominated (46%) by the genus *Tilia*.

The site selected for the study was at Lindholmsallén including cross-streets Pumpgatan and Götaverksgatan, located on Hisingen, Gothenburg (57°45′N 11°54′E; Figs. 1 and 2). It has a broad range and an even distribution of varying fractions of permeable ground surface below the tree crowns, while other planting conditions and soil type are the same throughout the area. Lindholmsallén is a large alley with 409 *Tilia x europaea* trees. All trees were planted in 1999 in normal soil planting beds on top of construction waste. The ground surface layer immediately around the tree stems is covered with grass. This also applies for the cross-street Pumpgatan, while the surface layer at the other cross-street, Götaverksgatan, consists of gravel with some small patches of asphalt.

A total of 95 trees were measured in Lindholmsallén and its cross-streets. The trees were selected to achieve a broad range (19–100%) and an even distribution of the fractions of permeable ground surface below the tree crowns. Trees were not irrigated. They were trimmed during the first few years after planting on site to obtain natural crown shapes. In addition, large branches below 4.5 m height were removed to prevent disturbance of traffic, and new stem shoots below that height were removed for aesthetic reasons. All trees had approximately 0.20 m circumference (and were 8–10 years old) at the time of planting on site, and each tree has access to at least 16 m^3 of growing space (a pit of 4 × 4 m, 1 m deep) for the root system, which is the standard in Gothenburg (Pettersson 2006). A summary of tree traits measured in 2015 is provided in Table 1.

Tilia x europaea (common linden) is considered a hybrid between *Tilia cordata* and *Tilia platyphyllos* (large-leaved linden). It grows to a size of 20–25 m in height with a conical shaped crown. It is very commonly used in urban areas in Sweden, especially in older alleys and parks (Bengtsson 2000). Figure 1 displays an alley of *Tilia x europaea* at Lindholmsallén, Gothenburg.

Field measurements

Field measurements were conducted during 3 weeks in late September to early October 2015, and current-year shoot measurements were repeated during 1 week in late august 2016.

Stem circumference and diameter at 1.30 m above ground and current-year shoot length were used as long- and shorter-term indicators of tree growth, respectively. Current-year shoot length is a tree trait commonly used for assessing the vitality of trees in urban areas, routinely used by the municipal Parks and Nature Management unit in Gothenburg.

The lengths of 3 south-facing current-year shoots on each tree were measured as far up in the crown as possible; typically about one third up in the crown as seen from below, but still quite well exposed to solar radiation due to little shading from neighboring trees. Extendable gardening shears were used to detach the branches with current-year shoots at approximately 6 m height.

The mean annual stem diameter increment was calculated, assuming that all trees had 20 cm stem circumference at the time of urban planting, which is the standard in Gothenburg. Given that stem diameter and circumference had increased more than threefold until 2015 (Table 1), the uncertainty in the estimates of diameter increments should be rather small. In addition, tree height was measured for a subset of 10 typical trees at each site using a laser rangefinder, but this tree trait was not used in the analyses to assess impacts of ground surface permeability.

Table 1 Tree traits measured in 2015

Tree trait	Mean ± SD Range (min – max)
Year of planting	1999
Tree height (m)	9.0 -
Stem circumference (cm)	68.9 ± 7.3 49.5–84.5
Stem diameter (cm)	21.7 ± 2.2 16.0–27.0
Crown diameter (m)	6.5 ± 0.8 4.6–8.1
Average fraction of permeable surfaces within the vertically projected crown area (%)	71.7 ± 22.0 19.0–100.0
Average fraction of permeable surfaces within 1.5 times the vertically projected crown area (%)	57.8 ± 25.5 8.0–100.0

The table displays the mean values, standard deviation and the 0.05 and 0.95 percentiles. Since approximate tree height was measured in only about ten trees at each site, data on percentiles and standard deviation are lacking for this trait. Stem circumference and stem diameter were measured at approximately 1.3 m above ground

The tree crown's vertically projected area was estimated by measuring the crown width in two perpendicular directions with a measuring tape. The shape of the crown was assumed to be circular and possible irregularities were not taken into account. The fractions of impervious (pavement) and permeable (grass or gravel mulch) surfaces within the vertically projected crown area were measured for each tree. This was also done for a 1.5 times larger ground area. The latter index captures also the effects of precipitation just outside the tree crown, which may be important since a substantial part of the precipitation intercepted by the crown is evaporated and thus does not reach the ground. Stem growth and current-year shoot growth were related to the fraction of permeable surface area within the vertically projected crown area, as well as to the 1.5 times larger ground area.

Statistical analysis

Linear regression analyses were conducted to test if stem and current-year shoot growth were significantly related to the permeable fraction of the ground surface below the tree (the vertically projected crown area, as well as a 1.5 times greater area), using IBN SPSS Statistics 24 software.

Fig. 1 *Tilia x europaea* at Lindholmsallén, Gothenburg

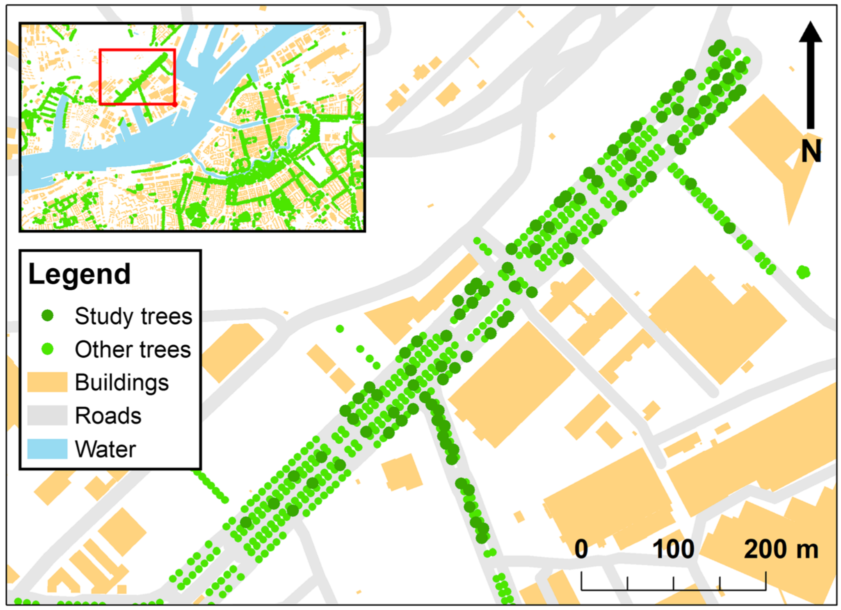

Fig. 2 Map showing the site and trees selected for the study

Results

Stem growth was weakly but statistically significantly related to the fraction of permeable surfaces at 1.5 times the vertically projected crown area at Site 1 ($R^2 = 0.05$; $P = 0.035$; Fig. 3a). A similar, but somewhat weaker relationship was found for the fraction of permeable surfaces of the vertically projected crown area (data not shown). Stem growth was approximately 10% lower for a tree with 10% of the ground surface (1.5 times below-crown area) being permeable compared to a tree with 100% permeable ground surface cover.

Current-year shoot growth was significantly related to surface permeability, again with stronger relationships using the 1.5 times the vertically projected crown area index (in 2015: $R^2 = 0.29$; $P < 0.001$; Fig. 3b) than for the vertically projected crown area (in 2015: $R^2 = 0.23$; $P < 0.001$; data not shown). The relationship was evident both years, even though the current-year shoot growth was half or less in 2016 compared to 2015. Also the relative influence of surface permeability on shoot growth was smaller in 2016 than in 2015. The current-year shoot growth reduction at 10% compared to 100% permeable ground surface (1.5 times below-crown area) was 55% in 2015 and 39% in 2016.

It is evident from the comparatively low R^2 values above (≤0.29) that other factors than surface permeability caused large variation in stem and current-year shoot growth among trees. Part of this variation may have been caused heterogeneous environmental conditions both above and below ground. Ideally, both soil moisture and soil texture should have been measured for each tree, but this was not possible with the available resources. However, all trees grew under broadly homogeneous conditions above ground and were planted in normal soil planting beds, allowing for the detection of significant effects of surface permeability on both stem and current-year shoot growth.

Discussion

A total of 95 linden street trees studied at two sites in Gothenburg, Sweden, were studied during two consecutive summers, with the aim to assess the importance of ground surface permeability on the vitality and growth of urban street trees. The results demonstrate that a low degree of surface permeability markedly decreases current-year shoot growth and to a lesser extent also stem growth. These findings are relevant to the development of improved planting designs for street trees, which have to endure both the harsh urban environment and ongoing climate change.

The site and tree selection—with 95 trees of the same species and age, growing under broadly homogeneous conditions except for their large variation in permeable ground surface cover—made this study well suited for studying the effects of surface permeability on street tree growth. The results show that an increasing fraction of permeable ground surface cover had a significant and positive effect on both tree stem and current-year shoot growth (Fig. 3). The effect on shoot growth was observed both in 2015 when the spring and summer were exceptionally wet, and in 2016 when the spring and early part of the summer were unusually dry. These results thus indicate that a higher degree of surface permeability is beneficial to street tree growth over both short (yearly) and long (decadal) time scales.

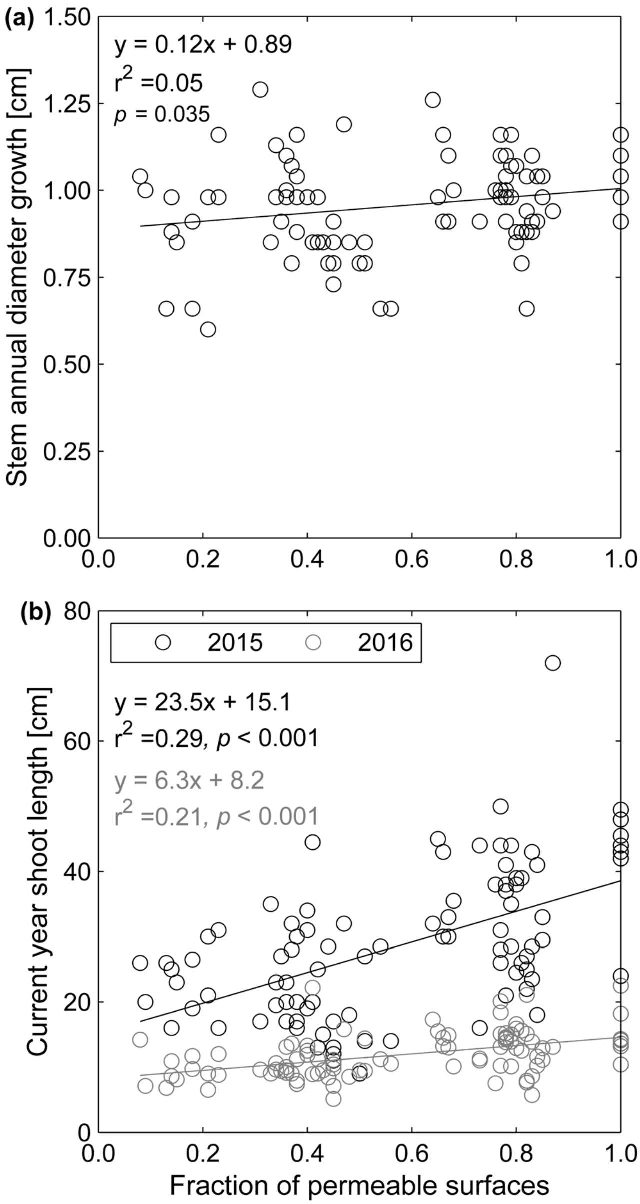

Fig. 3 The relationship between the fraction of permeable surfaces in the 1.5 times vertically projected crown area (x-axis) and (**a**) stem annual diameter growth or (**b**) current-year shoot length

Our findings of positive effects of surface permeability on stem growth and current-year shoot growth (Fig. 3) are in agreement with earlier reports of positive influences of surface permeability on tree vitality, growth and transpiration (Celestian and Martin 2005; Ferrini and Baietto 2007; Grabosky and Gilman 2004; Iakovoglou et al. 2001; Jim 1997; Konarska et al. 2015; Quigley 2004; Roberts 1977; Sanders et al. 2013; Schröder 2008). This effect was probably in part due to the combined effects of better soil aeration (Wiseman 2004), higher soil microbial activity and nutrient release (Gemtos and Lellis 1997), and a cooler and moister belowground and aerial environment immediately surrounding the trees (Celestian and Martin 2004; Graves 1994; Montague and Kjelgren 2004; Mueller and Day 2005). However, the greatest contributing factor was likely the increased water availability that a greater proportion of permeable surface cover affords the trees. Tree water supply obviously has a very strong influence on tree growth, as shown by the considerably larger current-year shoot growth in the wetter 2015 compared to the drier 2016. Most of the current-year shoot growth of linden occurs during the spring and early summer, and precipitation in Gothenburg during March–May was 150% higher than normal (1961–1990) in 2015 and 25% lower than normal in 2016 (SMHI 2015, 2016).

Not only was current-year shoot growth in general higher during the wetter year 2015, but also the relative effect of surface permeability on shoot growth was unexpectedly stronger in the wet 2015 than in the drier 2016. This shows that rather than diminishing the positive effects of higher surface permeability by providing all the trees with a plentiful supply of water, more rainfall actually magnifies the benefits of surface permeability – at least up to a possible limit that was not reached in this study. A possible reason for why the effect of surface permeability on shoot growth may be smaller in a dry year is that such a year may include predominantly shorter and less intense rain events during which a larger fraction of the rainfall is intercepted by the tree crown. Rain events during March to May were indeed less intense in 2016 than in 2015 in Gothenburg.

The size of the permeable surface area around a tree had a considerably stronger positive effect on current-year shoot growth (Fig. 3b) than on stem growth (Fig. 3a). A possible explanation for this difference is that the two response variables have different time scales. Annual stem growth was estimated as the mean value since planting, while shoot growth was measured for a recent and specific year. The estimates of stem diameter increment thus include also years when the trees were younger and smaller, when the importance of permeable surface size may have been lower than today.

Conclusions and implications

The results of this study have shown that trees with a small fraction of permeable surfaces below the tree crown have strongly suppressed shoot growth (−39% to −55%) and somewhat reduced stem growth (−10%). We thus conclude that the use of permeable surface materials is beneficial for the vitality and growth of urban linden trees in Gothenburg, and likely also of other tree species planted along streets in other cities.

Acknowledgments The project was funded by the Swedish Research Council Formas, Mistra Urban Futures, and the Swedish Transport Administration (259-2012-887). Special thanks are due to Mats Räntfors and William Persson Öberg for help with fieldwork, as well as to Eva-Maria Hellqvist at the Parks and Nature Management unit of the City of Gothenburg for providing valuable data. The two last authors were supported by the Swedish strategic research area Biodiversity and Ecosystem Services in a Changing Climate (BECC; www.becc.lu.se).

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